Property Protection from Extreme Bushfire Events under the Influence of Climate Change

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March 2017

Submitted for the degree of Doctor of Philosophy at the Western Sydney University, Sydney, Australia

Statement of Authentication

The work presented in this thesis is to the best of my knowledge and belief, original except as acknowledged in the text. I certify that I have not submitted this material, either in full or in part, for a degree at this or other institution.

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Acknowledgements

This project commenced when I was working with the New South Wales Rural Fire Service (NSW RFS). The project arose to answer three key questions. These were:

a) how to apply the principles of recurrence to bushfire events and bushfire behaviour in developing the concept of the 'design bushfire' for land-use planning and construction practice;
b) to ascertain whether there was any short or medium term shifts in recurrence of fire weather arising from climate change; and
c) to compare two forest fire behaviour models (McArthur vs Project Vesta), at the extreme of fire weather, in terms of rates of forward spread and flame height, and its implications for land-use planning and construction practice.

These questions arose because of earlier work by Hennessey et al (2005) and the outcomes of Project Vesta (Gould et al, 2007). There was no clear methodological approach in developing the concept of the design bushfire, although I had pondered the problem with others prior to this (Douglas and Tan, 2005). In 2001, the Australian Standard, AS 3959-1999, was amended to include a bushfire attack level of EXTREME, which amongst other things, allowed what on the face of it, was inappropriate construction within mm's of high hazard bushfire conditions. In the 2001/02 bushfire season, significant house losses were experienced and the document *Planning for Bushfire Protection (2001)* was released to address some of the concerns arising from the Australian Standard. I lead the policy changes necessary to implement the planning document and AS3959 in NSW, but I had concerns that the question of design bushfire was not being adequately considered.

The Hennessey et al (2005) report lead to preliminary outcomes for the design bushfire in the NSW RFS document *Planning for Bush Fire Protection* in 2006, of which I was the lead author. Prior to commencing this project, no literature on the determination of extreme bushfire events for land use planning had been identified. Nor had there been any clear application of flame heights from Project Vesta although operationally, rates of spread had been well developed.

In addition, the NSW RFS provided access to mapping and data of vegetation formations (Keith, 2004), subsequently also available on-line through the Office of Environment and Heritage.

As such, I wish to acknowledge the assistance of the NSW RFS in allowing me to pursue these questions through undertaking this study. Since commencing, the study has expanded somewhat, as has the aim and objectives now listed in Chapter 1.However, the study would not have commenced without the support of the NSW RFS and its staff. I particularly want to thank Dr Billy Tan of the NSW RFS for his guidance and support who helped in developing my ideas and was an invaluable source of information.

I am also indebted to some early support of the Bushfire Cooperative Research Centre, which has subsequently evolved into the Bushfire and Natural Hazards CRC. They provided some financial support to attend the Bushfire Research Forums during my early studies, where I was able to test my ideas and obtain peer review and support.

To my supervisors I am truly indebted, and most especially to Dr Yaping He, who has been my principal supervisor for the last four years, and to Professor Yang Xiang (my early principal supervisor) and Assoc.Professor Charles Morris in assisting and supervising my work. These people have been colleagues and through them I have published a number of papers which have led to the final product, this study. As such, I wish to thank Western Sydney University for granting me the opportunity to undertake this investigation, whilst engaging me to teach in the post-graduate bushfire program through the School of Computing, Engineering and Mathematics.

During the period of investigation, many issues have emerged, including the need to obtain high quality weather data. To this end, the Bureau of Meteorology has assisted in supplying data. The initial data that was available provided a number of weather stations developed by Lucas (2010) under the National Historical Fire Weather Dataset. Additional weather station data was developed by myself for additional weather stations which was used to replicate the work of Lucas (2010) for a number of additional fire weather districts in NSW. The original data only covered the period up to 2009, but in early 2016, additional data was obtained to extend the data to 2015. As such, the early work comprised a smaller period than later investigations. This additional data allowed for improved studies of climate change, not available at the commencement of the study. As such, I wish to acknowledge the assistance of the Bureau of Meteorology in making this study possible.

Early on in the study, it became apparent that to complete the study effectively, I would need access to data on vegetation fuel characteristics. This work was largely undertaken by Dr Penny Watson and a team from the University of Wollongong, whose reports on Keith

(2004) vegetation classes allowed me to compare fire behaviour between the McArthur Fire Danger Meter Mark 5 equations with those of Project Vesta. I had assisted Dr Watson in her doctorate studies and she has returned the favour with her timely work.I have been able to compile a more comprehensive fuel characterisation of forest vegetation because of this work. For this I am grateful.

Dr Jim Gould formerly of the CSIRO and Dr Andrew Sullivan currently with the CSIRO provided some early tips and copies of papers, including up to date information on fire behaviour and Project Vesta. I thank them for their assistance.

I have also been encouraged by my many friends and colleagues, including Mark Chladil, Phil Redpath, Colin Wood, Douglas Brown and Stuart Little, who have lent support to my endeavours. I can now also thank my examiners (Prof David Keith and Dr Alexandra Syphard) for their constructive review, remarks and the nature of the positive feedback as well as an acknowledgement of the importance of this work.

As the project was undertaken part-time and over 8 years, there are numerous people to thank and acknowledge. Inevitably I will miss some of these people and apologise for any neglect on my part. However, there are some people I cannot possibly ignore. These are my family members who have supported me through this long and arduous period. In particular, I wish to acknowledge and thank my wife Sally Zhang for her tireless support whilst I progressively neglected my work at home, leaving her to pick up these tasks while I studied and furiously attempted to get clarity in my thoughts and discovery of new knowledge and ideas. I am truly indebted to her patience and love.

Grahame Douglas
March 2017.

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Glossary and Acronyms.

Term	Description
Bushfire attack	Burning embers, radiant heat, wind or flame generated by a bushfire, which might result in the ignition and subsequent damage or destruction of a building.
Bushfire Intensity	The heat generation rate by a bushfire which is measured in kilowatts per linear meter (kW/m) of fire front.
Bushfire prone area(s)	Means land which has been designated under legislation as being subject, or likely to be subject, to bushfire attack.
Consequences (of bushfire)	The potential loss or damage of buildings (structures), life and the environment arising from bushfire attack. Critical radiant heat conditions arising from a bushfire.
Design bushfire	The dimensions and characteristics of a bushfire flame, its initiation, spread and development, which arises from assumed weather conditions, topography and fuel (vegetation) in a given regional setting. It can be used to determine consequences and radiant heat.
Fire weather frequency	The number of days within a given period (annual or seasonal) which exceed a threshold value for a fire weather parameter.
Forest fire danger index (FFDI) - also grassland fire danger index for grasslands (GFDI)	An indicative and empirical measure of *"the chance of a fire starting, its rate of spread, its intensity and the difficulty of its suppression, according to various combinations of air temperature, relative humidity, wind speed and both long and short term drought effects (using the equations of Noble et al 1980)"* – AS3959-2009.
Keetch-Byram Drought Index (KBDI)	Is a measure of soil dryness (ranging from 0-200 mm of soil moisture deficit) and is used as an input to calculate FFDI.
Performance	A set of conditions (such as a verification method) which meets either the performance requirements of the BCA or the performance criteria for a planning objective.
Recurrence period	The likely interval between the same weather conditions in which bushfire events can occur of a given severity. (Measured as 1 in x years intervals – e.g. 1:50 years) (also called return period/annual return interval)
Recurrence value	The value of a parameter with a specified recurrence period.
Severity (of bushfire)	The expected consequences of a bushfire event in terms of degree of injury, property damage, or other mission impairing factors should that occur.
Severity (weather)	The weather conditions which give rise to bushfire intensity (should ignition occur) given set fuel loadings of a forest, woodland, heath, grassland or other vegetation.
Verification method	Means a test, inspection, calculation or other method that determines whether a building solution complies with the relevant 'Performance Requirements' of the Building Code of Australia.

Abbreviations

ABCB	Australian Building Codes Board
Amax	Annual Maximum (Gumbel) Distribution
Amin	Annual Minimum (Gumbel) Distribution
BAL	Bushfire Attack Level
BCA	Building Code of Australia (Vols. 1 & 2 of the NCC)
BoM	Bureau of Meteorology
DEFFM	Dry Eucalypt Forest Fire Model (Project Vesta Model)
DJF	December-January-February
ENSO	El Nino/Southern Oscillation (seasonal -ve SOI)
EVA	Extreme Value Assessment (statistical)
extreme	Extreme in common usage
extreme	Statistically extreme at a recurrence of $\geq$1:1 years
EXTREME	Extreme **rating** (e.g. FFDI>75, previously FFDI>50)
FFBT	Forest Fire Behaviour Tables (WA)
FFDI	Forest Fire Danger Index
FFDM5	(McArthur) Forest Fire Danger Meter Mark 5 (Model)
FMC	Fuel Moisture Content (%)
GCM	Global Climate Model used as a predictive tool for weather.
GEV	Generalised Extreme Value Distribution
GEV_{50}	Generalised Extreme Value @ 1:50 year recurrence interval
GFDI	Grassland Fire Danger Index
GPD	Generalised Pareto Distribution (GPD_{50} @1:50 year recurrence)
IOD	Indian Ocean Dipole
IPCC	International Panel on Climate Change
KBDI	Keetch-Byram Drought Index (mm)
NA	Not Applicable
N/A	Not Available
NCC	National Construction Code
NSW	New South Wales
NVI	Native Vegetation Inventory (Cwlth)
OEH	Office of Environment and Heritage
RFS	Rural Fire Service
RH	Relative humidity (%)
ROS	Rate of (forward) spread
S.D. (s.d.)	Standard deviation
S.E. (s.e.)	Standard error
SOI	Southern Oscillation Index
Tmax	Maximum Temperature (C^0)
∑FFDI	Cumulative (sum) of FFDI. Also applied to FMC and KBDI

Nomenclature

Equation nomenclature

Bf	Bias adjustment factor for flame height
Br	Bias adjustment factor for rate of spread
cm	centimetres
D	Drought factor
Et	Evapo-transpiration (mm)
F	Forest Fire Danger Index
FHS	Fuel hazard score (Subscripts s=surface, ns = near surface, b = bark)
FMC	Fuel Moisture Content (%)
Ha	Hectares
He	Height of elevated fuel
Hns	Height of near surface fuel in cm
Hs	Height of shrubland (or scrub) in metres
I_b	Fire line intensity (Byram)
KBDIi	Today's KBDI
KBDIi-1	Yesterday's KBDI
kph	Kilometres per hour
m	Ranked value (plotting position)
m/mm	Metres/millimetres
MC	Moisture content for surface litter
n	Number (years of data)
N	Number of days since rain
NS_{fhs}	Near-surface fuel hazard score
NS_h	Near-surface fuel height (cm)
P	Daily Precipitation (mm)
Peff	Effective precipitation (mm)
R	Rate of Spread (general) (kph or m/hour)
Rd	Radiant heat (kW/m^2)
Rfm	Rate of Spread adjusted for fuel moisture
Rm	Rate of Spread (McArthur) for FFDM5 (kph)
Rv	Rate of Spread (Project Vesta) for DEFFM
Rwa	Rate of Spread (FFDT)

RH	Relative Humidity (%)
S	Slope of the Trend line (parameter α to express trend)
S_{fhs}	Surface fuel hazard score
T	Return period (recurrence)
T	Temperature ^{0}C
Tmax	Maximum Temperature ^{0}C
U_{10}	Wind speed at 10 m above ground (kph) Average over 10 minutes
U_{ave}	Average of wind speeds
U_t	Threshold wind speed of 5 km/hr. @ 10 m above ground (kph)
W_t	Weight of fuel (tonnes per Hectare)
W	Weight of total fuel (understorey and canopy)
w	Weight of understorey fuels
Z	Flame height
Zl	Flame length
Zm	Flame Height (McArthur) for FFDM5
Zma	Adjusted Flame Height (McArthur)
Zv	Flame Height (Project Vesta) for DEFFM

Scientific and Mathematical

α	Shape parameter (linear or logarithmic equations)
β	Intercept parameter (linear or logarithmic equations)
β_1	Shape parameter for GPD (same as α in GEV)
ε	Flame emissivity when used in Stephan-Boltzman equation
exp	exponential
r	Pearson's Correlation Coefficient
r^2	Correlation Coefficient (square)
t	Transmissivity of air between emitter (flame) and receiver
T_k	Flame temperature (in degrees Kelvin)
φ	View factor
σ	Stephan-Boltzman constant (5.67 x 10^{-11} $kWm^{-2}K^{-4}$)
χ2	Chi squared (used in chi squared test)
∞	Infinity
∑	Cumulative (sum of)

Vegetation and Fire Weather Districts

Vegetation

DSF	Dry Sclerophyll Forest
DSFg	Dry Sclerophyll Forest - Grassy/Shrub sub-formation
DSFs	Dry Sclerophyll Forest - Shrubby Sub-formation
WSF	Wet Sclerophyll Forest
WSFg	Wet Sclerophyll Forest
WSFs	Wet Sclerophyll Forest
GW	Grassy Woodland
NC-DSF	North Coast Dry Sclerophyll Forest
NC-WSF	North Coast Wet Sclerophyll Forest
NH-WSF	Northern Hinterland Wet Sclerophyll Forest
SydC-DSF	Sydney Coastal Dry Sclerophyll Forest
SE-DSF	South East Dry Sclerophyll Forest
ST-DSF	Southern Tablelands Dry Sclerophyll Forest
HM-DSF	Hunter Manning Dry Sclerophyll Forest
Cu-DSF	Cumberland Plain Dry Sclerophyll Forest
CV-GW	Coastal Valley Grassy Woodland

Fire Weather Districts (see Table 5.2)

FNC	Far North Coast
NC	North Coast
GH	Greater Hunter
GS	Greater Sydney Region
IS	Illawarra/ Shoalhaven
FSC	Far South Coast
MA	Monaro Alpine
ACT	Australian Capital Territory
SR	Southern Ranges
CR	Central Ranges
NE	New England
NS	Northern Slopes
NW	North Western
UCW	Upper Central West Plains
LCW	Lower Central West Plains
SS	Southern Slopes
ERi	Eastern Riverina
SRi	Southern Riverina
NRi	Northern Riverina
SW	South Western
FW	Far Western

Wind Direction

Symbol	Bearing	Degrees
N	North	360
S	South	180
E	East	90
W	West	270
NE	North-east	45
NW	North-west	315
SE	South-east	135
SW	South-west	225
NNE	North-north-east	22.5
NNW	North-north-west	337.5
SSE	South-south-east	157.5
SSW	South-south-west	202.5
CALM	Calm conditions (zero wind speed)	N/A

Abstract

Natural disasters give rise to loss of life, property (including homes, industry and livelihood) and environmental values and may be increasing with the impacts of climate change. Bushfires are a natural part of the Australian landscape and the ecology of the range of biota found within the various landscapes. They pose significant risks to people and property and require increasing demands for management in the face of these risks.

Bushfires (also known as wildland fires) can be highly complex both spatially and temporally within the landscape. Attempts to better explain such events has given rise to a range of fire behaviour models to quantify fire characteristics such as rate of spread, fire line intensity, flame heights and spotting distances. However, there is a need to develop clear criteria when applying these models in land use planning and construction practice for bushfire protection.

In Australia, a number of empirical models have been developed to quantify bushfire behaviour. These models have limitations, both in their application and in their capacity to draw upon data with which to utilise them. Two such models are used in the current study, being the McArthur Forest Fire Danger Meter (Mark 5) and the more recent Dry Eucalypt Forest Fire Model, and both have been used to develop *design bushfire*(dimensions and characteristics of a bushfire in a regional setting) conditions for the state of New South Wales (NSW). These models use different input parameters, as well as different intermediate parameters to describe fire behaviour.

In addition, the study utilises and extends the forest fire danger index (FFDI) andKeetch-Byram Drought Index (KBDI) data to all 21 NSW fire weather districts. It also provides a new database for daily fuel moisture content (FMC).

By using case studies that show 'validation' of methodological approaches, it can be confirmed that suitable *extreme* value assessment statistical techniques can be applied to the outputs of the identified models for the purposes of determining design bushfires.

The study also seeks to give greater understanding of the frequency and shifts in the seasonality of fire weather, and changes in bushfire severity as consequences of climate change. A technique of generalised extreme value analysis based on moving data window to detect the impact of climate change on recurrence values of various indices has been

developed. The evaluation of trends in fire weather through various metrics for FFDI, FMC and KBDI have revealed that a number of districts in NSW exhibit pronounced shifts at the *extreme* arising from climate change. However, the role of the El Nino Southern Oscillation does not appear to play a major role in these shifts over the long term.

The current investigations have provided significant improvements on previous investigations such as improved datasets providing wider representation of all the NSW fire weather districts and covering a longer period of time; the use of new metrics, including the use of the GEV assessment through a moving period approach; the metrics being applied to fire weather parameters other than FFDI; and, trends in fire weather parameters being considered in conjunction with other global factors.

The methodology and the technique developed in the current study have the potential to be utilised in many parts of the world for the development of design conditions and to study the impact of the climate change on the local fire weather conditions.

CHAPTER 1-INTRODUCTION

1.1 Context

Bushfires, or wildland fires, are closely related to weather conditions and patterns of fuel. There have been concerns that global warming could have an increase in the effect on bushfires within fire prone landscapes (Fried et al, 2008; Flannigan et al, 2009; Wotton et al, 2010; Clarke et al, 2011). This in turn may result in increasing risk to building developments and living in bushfire prone areas. It is quite possible that climate change will alter the bushfire pattern in terms of frequency and severity (Cary, 2005). How climate change should be considered in the evaluation of fire behaviour is still a question that has not been fully addressed.

The contemporary concern with bushfires arises from three major fields or paradigms as summarised by Pyne (2007):

i. the physical dimensions of bushfire and its management (control) across the landscape,

ii. the impacts that bushfires have on elements of biodiversity within the landscape, and

iii. the impact of these fires on the social (cultural) arrangements of society, including loss of life and economic assets.

Research that brings together and develops synergies from the interaction of the physical, biological and cultural aspects of bushfire research will deliver an improved understanding of bushfire and its impacts for communities. In the context of fire research, the current study seeks to recognise this inter-dependency when considering fire weather, fuel and human occupation within the landscape.

When addressing any question related to bushfire protection of life and property, one must consider not only bushfire weather (the focus of the current investigation) but also the topographical features, vegetation characteristics (fuel), previous treatment options (such as hazard reduction) and the socio-economic context of bushfire in the landscape (Haight et al, 2004; Gude et al, 2008).

Bushfire weather can be seen as the meteorological conditions which give rise to bushfire events. These meteorological conditions include (but not limited to) temperature, relative humidity, wind speed and rainfall all of which affect fuel moisture and can be expressed in terms of a fire index (Sullivan et al, 2012).

Importantly, fire behaviour models using these meteorological conditions and indices have been developed in an attempt to predicatively quantify flame characteristics (such as flame height or flame length) for a bushfire. Such flame characteristics can then be used to derive a level of protection from bushfire attack, especially from radiant heat and flame contact (Douglas and Tan, 2005). However, these meteorological input parameters to such models have been generalised and largely unquantified (Douglas et al, 2013) at the extreme, warranting an investigation as to the appropriateness of these to assist in developing a suitable statistical approach to these conditions.

Internationally, recent research focus is shifting towards the risk-based approach to bushfire (or wildfire) management (Miller and Ager, 2013). The impact of climate change has also been considered under this kind of approach (Good et al., 2008).In the case of bushfire weather conditions, the quantification of risk has been difficult to address (Bradstock et al, 2003). Such models can only assist in determining the appropriate levels of construction practice where specific conditions are known (Douglas et al., 2006). In relation to the quantification of fuel characteristics as inputs to fire behaviour, recent work in NSW has provided the opportunity for the compilation of likely fuel components, although such a compilation has not yet occurred (Watson, 2009).

1.2 The Bushfire Problem in Australia

Bushfires (wildland fires) are a common occurrence across the globe with many countries reporting significant fire events and property losses (Cohen, 2000; Alexander, 1982; Amiro et al, 2004). In the context of the Australian landscape these losses are particularly true in South East Australia comprising the States and Territory of New South Wales (NSW), Australian Capital Territory (ACT), Victoria (Vic), Tasmania (Tas) and South Australia (SA) (Teague et al, 2010). There are likely to be bushfires burning somewhere in continental Australia at any point in time, although the seasonal distribution of bushfire varies widely. Most bushfires are dealt with and controlled by the various fire services and land management agencies at the early development stage.

Bushfires are characterised by both spatial and temporal elements which are difficult to predict over the long term. Extreme bushfires may occur as single or concurrent fires under conditions of high fuel loads (vegetation), weather, and relief (topography). These more extreme fire events that can cause major losses to life, property and the environment are less common, but occur with some regularity or recurrence (Alvarado et al, 1998). Such extreme bushfire events are often unpredictable in nature and are of high intensity, making control difficult. While bushfire may occur in grasslands, heaths (scrublands), woodlands or forests, major events associated with forest fires give rise to the greatest concern in Australia largely due to the higher fuel loads and characteristic canopy fires associated with forests (Bradstock et al, 1998).In the US, shrublands and other types of vegetation are considered equally hazardous and give rise to significant losses (Keeley, 2002).

A number of common factors contribute to the severity of consequences arising from fire events (Sullivan, 2004). These include:

- Antecedent rainfall deficit (especially for forest and related fires);
- Strong hot gusty winds associated with synoptic weather patterns and unstable atmospheric conditions directing winds from the central regions of continental Australia;
- Low fuel moisture resulting from sustained periods of drought, lower humidity and higher diurnal temperatures; and
- Pre-existing fires may be burning prior to the arrival of extreme weather conditions (including arson or poorly managed hazard reduction).

Under such conditions, considerable areas of land can be burnt, which may lead to significant damage to resources, environmental values and/or built assets. Of greater interest to the community (as expressed through media and political leaders) is the significant likelihood of losses to life and economic property assets (Ashe, et al 2009). The 7 February 2009 bushfires in Victoria (Victorian Royal Commission, 2009) brought such events into stark relief and highlighted the human and economic costs associated with these bushfires.

The COAG report "*Economic Costs of Natural Disasters in Australia*" (Gentle et al, 2001) identified that in the period 1967-1999, bushfire ranked 5th behind flood, severe storm, tropical cyclone and earthquake in terms of total and insured costs to the community.

While NSW was ranked highest in terms of costs of natural hazard events on the community, these costs were more likely to be associated with floods and storms. It is of interest to note that for the ACT the major costs were associated with bushfire (COAG, 2002).

Over the last hundred years, the average house losses associated with bushfire in Australia is estimated at 83 homes per year (Ashe et al, 2009). Most of these losses occurred within south-eastern States (NSW, Victoria, South Australia, ACT and Tasmania). The most severe of these events in Victoria (7 February 2009) have seen the loss of 173 lives, the loss of over 2100 homes and the dislocation of over 7,000 residents impacted (Teague et al, 2010). Combined with the consequences of the 2003 fires in the ACT (McLeod, 2004), and recent fires in Tasmania (2013) and Western Australia (Keelty, 2011) these bushfire events represent major insurance losses, without taking into account losses of heritage value, environmental assets, businesses, and of life.

McAneney et al (2007) provides a list of losses arising from bushfires. The study considered nearly 5,000 bushfire events from 1900 to 2003 and identified an average of 84 buildings lost per annum, with some 2,300 lost in one event cluster (actually 100 separate fires) during the Ash Wednesday fires of 16 February 1983. On 5 occasions since 1926, 500 or more buildings were destroyed during a single event. In context, the major fire events were Black Friday in 1939, Hobart 1967, Ash Wednesday 1983 (47 lives lost), Sydney 1994 and Canberra 2003. However, these events were certainly overtaken in magnitude and loss by the events of 7 February 2009 (Black Saturday) in Victoria (Grace, 2009).

Such losses can draw significant public interest and demands for action at various levels of Government and industry. Such responses include increased accountability of land managers in relation to fire management, increased controls on developments in bushfire prone environments (including construction standards) and addressing environmental considerations in the face of perceived delays in implementing effective mitigation strategies (Douglas, 2002).

Major events inevitably lead to major formal inquiry processes. After the 1994 Sydney fires, there were three major inquiries. These were a Cabinet sub-committee inquiry, a Parliamentary inquiry and a Coronial Inquest, all of which made recommendations for various changes, subsequently implemented by the NSW Government (Little, 2002).

Of interest, are the findings and recommendations of the 2002 NSW Parliamentary Inquiry (after the 2001 bushfires in NSW) (Joint Select Committee, 2002) which included the following terms of reference:

> *"(e) The adequacy or otherwise of building regulations currently in operation in New South Wales with particular emphasis on the Australian community bushfire safety standards for houses. ….*
> *(g) The adequacy of changes made to bushfire planning and fighting, development planning and other relevant matters since the 1994 bushfires."*.

The Inquiry Committee's final report made 70 recommendations to address a range of issues including the role of land-use planning, construction standards and hazard reduction as risk mitigation strategies (Joint Select Committee, 2002). The inquiry noted the deficiencies of the relevant Standards (AS3959, 1999) and the need to improve the role of land-use planning with appropriate construction for buildings in bushfire prone areas. As a consequence, the subsequent revision of AS3959-1999 incorporated an improved site assessment methodology proposed by Douglas and Tan (2005). The new version of AS3959 was released in 2009 in the immediate aftermath of the Black Saturday bushfires of 7 February 2009. However, determination of risk through the quantification of a suitable and consistent fire weather consideration was not adequately considered in finalising the document (Douglas, et al, 2014).

In the context of the Black Saturday fires of 7 February 2009 in Victoria, the Victorian Government appointed a Royal Commission with wide ranging terms of reference including (Victorian Royal Commission into Bushfires, 2009):

> *"6. The preparation and planning for future bushfire threats and risks, particularly the prevention of loss of life.*
>
> *7. Land-use planning and management, including urban and regional planning.*
>
> *8. The fire proofing of housing and other buildings, including the materials used in construction."* .

The Royal Commission made 19 recommendations in relation to planning and building controls for bushfire prone areas (Teague et al, 2010).

Recommendation 48 of the Royal Commission's Final Report: Summary included (the) *"Australian Building Codes Board do the following: ....*

> *Work with Standards Australia to effect expeditious continuing review and development of AS 3959, Construction of Buildings in Bushfire-prone areas, and other bushfire referred to in AS 3959-2009, and any other bushfire related standards referred to in the Building Code of Australia"*

Thirteen major inquiries have been conducted relating to NSW alone from 1994 to 2009 on bushfires with significant findings relating either to the NSW Rural Fire Service (or its predecessor), mitigation measures and controlling land-use/development (RFS, 2002). Many similar inquiries have also been undertaken in Victoria (e.g. after Ash Wednesday and the Victorian Royal Commission), South Australia (post 2005 fires;) the ACT (McLeod, 2005) and Western Australia (Keelty, 2011).

The high severity and frequency of bushfire events have drawn increased attention from both government and the general public. As a result, a number of bushfire protection reforms have been made first in NSW (RFS, 2006) and, in the wake of the Black Saturday fires, nationally (VBRC, 2010;Keelty, 2012). In the light of such public concern, media interest and political response to Black Saturday (Grace, 2009) and other major fire events there is a need to determine suitable input considerations in developing standards for assessing bushfire attack on buildings.

1.3 Bushfire Behaviour and Land use/Construction Practice

1.3.1 Building Code of Australia and construction practice

Building construction in Australia is regulated by the National Construction Code which comprises the Building Code of Australia (BCA) and the National Plumbing Code (ABCB, 2014). The Building Code of Australia is produced and maintained by the Australian Building Codes Board (ABCB) on behalf of the Commonwealth Government and each State and Territory Government.

The goals of the BCA are to enable the achievement and maintenance of acceptable standards of structural sufficiency, safety (including safety from fire), health and amenity for the benefit of the community now and in the future. These goals are applied so that the provisions of the BCA extends no further than that necessary in the public interest, cost effective, easily understood, and not needlessly onerous in its application. From a bushfire perspective, the BCA adopts Australian Standard AS3959-2009 as the deemed-to-satisfy provisions. Natural hazards such as flood, wind, earthquake and snow fall are based on recurrence or return periods for structural considerations within the BCA (ABCB, 2014).

For bushfire protection, it is stated in the BCA that when the deemed to satisfy solutions are sought, the Standard AS 3959-2009 *Construction of Buildings in Bushfire Prone Areas* should be referred to as the suitable construction manual.

1.3.2 Role of Australian Standards in bushfire protection

The construction of residential buildings need to comply with the Building Code of Australia and AS3959 -2009 which incorporates a site assessment methodology (ABCB, 2014). The purpose of the site assessment is to determine the category of bushfire attack level (BAL) to which a building might be exposed and the construction level required to compensate for this bushfire attack level. These issues are dealt with at greater depth in Chapter 2.

These BAL levels are based on fire engineering principles which incorporate fire behaviour calculations to determine radiant heat and flame contact. Key considerations in AS3959 (2009) for these models include bushfire weather components (expressed as FFDI and/or wind speed) and vegetation (as an expression of fuel) but not recurrence levels, as with the structural provisions for wind, snow and earthquake, etc.

These BAL levels are therefore dependent on the means of calculating the design conditions under which a building is anticipated to perform (from a bushfire perspective) under the Building Code of Australia. The concept of a design bushfire can be described as: *the dimensions and characteristics of a bushfire flame, its initiation, spread and development, which arises from assumed weather conditions, topography and fuel (vegetation) in a given regional setting. It can be used to determine consequences and radiant heat.*

1.3.3 Land use controls and fuel management

Planning and land-use controls are seen as the most effective way of improving community safety arising from bushfires and other natural disasters (EMA, 2002; COAG, 2002). In California, the State Board of Forestry and Fire Protection (2010) developed a strategic fire plan to prioritise defensible space and land-use controls in the wildland urban interface (WUI). In the aftermath of Ash Wednesday, work commenced on developing improvements in land-use planning and development controls in bushfire prone areas (Department of Urban Affairs and Planning, 1989) and guidelines for planning decisions (Department of Bush Fire Services, 1991).

These guidelines were improved in 2001 by incorporating a site assessment methodology. In 2006, the site assessment methodology incorporated fuel (vegetation) and fire weather parameters for use in a regional setting for NSW Fire Weather Areas (RFS, 2006). This latter document forms the basis of statutory development controls for developments in bushfire prone areas and identified a policy setting of a 1:50 year return period (or recurrence) for fire weather assessments.

Responses to land-use planning can be at the strategic level or at the site level when constructing in a bushfire prone environment. At the site specific level, there has been increasing emphasis on the use of defensible space (Syphard et al, 2014) and construction (Douglas and Ellis, 2000).

The role of fuel management in the landscape has been investigated and found to have minimal effect at severe fire weather conditions (Price and Bradstock, 2012; Bradstock et al, 2012) although some benefit may be available for recently treated areas of 5-10 years at more moderate conditions. Improved property preparedness and suppression resources resulted in greater reduction in house loss (Penman et al, 2015) however, little is known about the relative importance of construction practice in conjunction with land-use planning (Ellis, 2000).

1.4 Climate Change and Fire Weather in NSW

Fire is a natural phenomenon in the Australian landscape, however, the frequency, seasonality, extent and intensity of bushfires varies within that landscape (Gill, 2012). The pattern of fire regimes in Australia can demonstrate broad biogeographic variability, due to influences of biomass growth, availability to burn, fire weather and ignition sources (Bradstock, 2010).(see section 3.3 for further discussion).

Climate is a key driver of the emergence of the bushfire season. For Northern Australia, the monsoonal tropics dominate, whereas further south, climate is described as being Mediterranean in the mid-latitudes (Lucas, 2007).

Climate change arises from both anthropogenic and natural sources of emissions and includes not only carbon dioxide, but also methane and other greenhouse emissions into the atmosphere (Raupach et al, 2008).

The influence of climate change on fire regimes can vary within the landscape and can be distinguished from other factors such as increased CO_2 in the atmosphere or land-use changes associated with agriculture, forestry or urbanisation (Bradstock, 2010).

Carey (2005) in considering research priorities for bushfire in South-East Australia included how climate change and the development of optimal solutions to the management of bushfire risk as key areas of research. He observed that the events of the 2002-03 bushfire season had given rise to speculation that such events were a result of climate change. The events of South Australia (in 2005) and Victoria (2009) have reinforced such a view. Carey notes that "…. *research to date suggests that fire danger and fire regimes are sensitive to potential changes resulting from climate change*."

However, much of the work is based on predictive models assuming changes in CO_2 levels will give rise to various outcomes. Even so the distribution of predicted changes across S.E Australia is not uniform (Carey, 2005 and Williams et al, 2001).

Still quoting from Carey (2005), he observes " … *there remains a need for the development of optimal mixtures of management options, across a diversity of ecosystems, which address these (often conflicting) constraints …(and) will require a range of methodologies including simulation modelling, insights from landscape fire ecology projects and statistical analysis of fire occurrence*..".

Figure 1.1 provides an overview of the statistical trend in maximum temperature across continental Australia, over a period of nearly 100 years. This shows that increases in maximum temperature has been observed across most of NSW, however such changes are not uniform, nor are they only towards hotter conditions. Likewise, Figure 1.2 illustrates the patterns of rainfall trends over a similar period, and areas with increasing maximum temperatures may also exhibit increased rainfall.

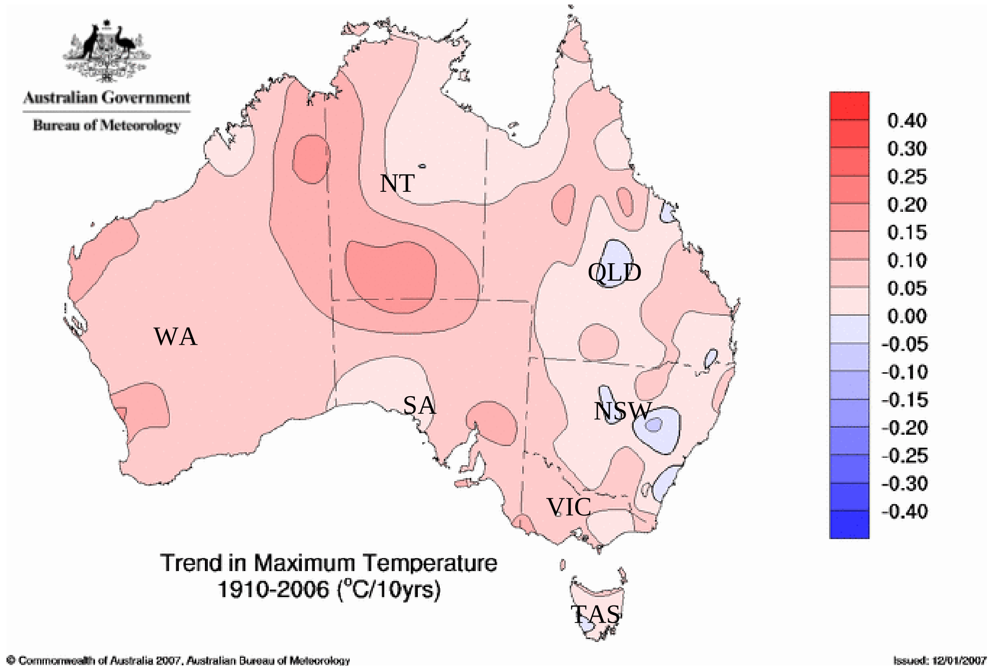


Figure 1.1: Trend in Maximum Temperature (1910-2006) (BoM website, 2007)

This figure indicates that some districts in NSW, notably the far north coast and far south coast are seeing an increase in rainfall, with a rise in maximum temperatures. In contrast, northern Queensland and south-west Western Australia are trending to drier conditions, with increasing maximum temperatures. For NSW the conditions are more complex.

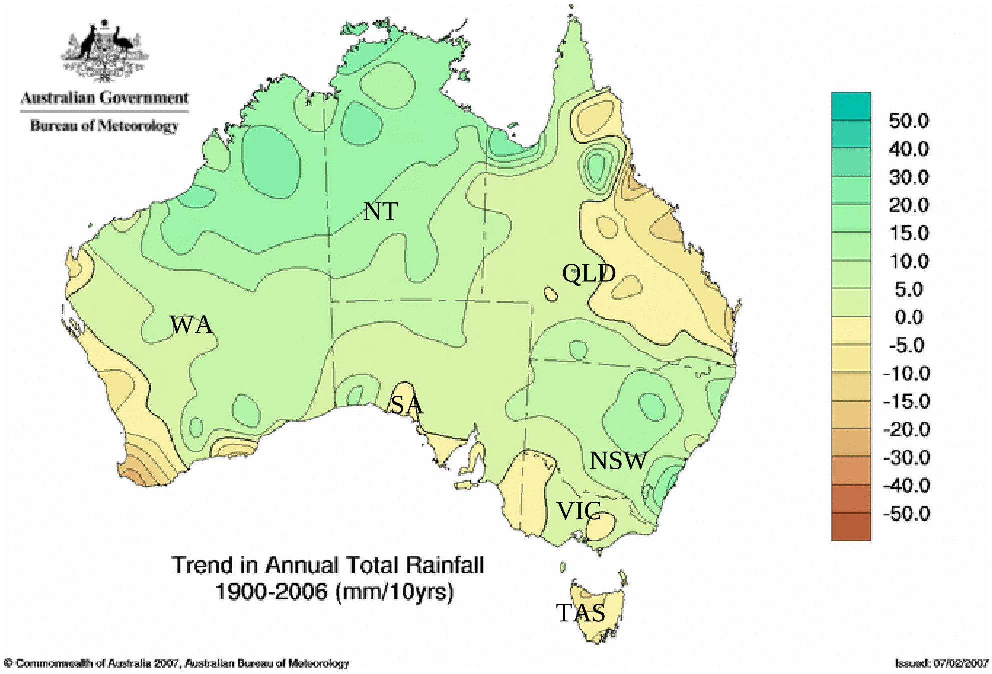


Figure 1.2: Trend in Annual rainfall (1900-2006) (BoM website, 2007)

In many countries, bushfire (wildland fire) behaviour has been linked to various fire danger rating systems, such as those in the USA, Canada, Portugal and Australia (Sullivan 2009b). In context, while extensive work has been undertaken to relate bushfire risk in Australia (Verdon et al, 2004), Canada (Cruz et al, 2003; Abbott et al, 2007; Beverly and Wooton, 2007), USA (Hardy and Hardy, 2007) and Europe (mainly Greece & Italy – Good et al, 2008, and Portugal - Fernandes, 2001) to various fire danger index systems, the relationship of such indices appears useful in determining fire size and 'sustaining fire', but is less relevant for determining likelihood of ignition. Fire danger ratings are used for bushfire warning systems such as total fire bans in NSW (RFS, 2009). In Australia, the Forest Fire Danger Index (FFDI) is commonly used as a measure of fire weather conditions, whereas in North America the Canadian Fire Weather Index and US National Fire Danger Rating System incorporate a fuel component as well.

One measure of altered fire weather (climate) is to compare the monthly or seasonal cumulative maximum forest fire danger index (∑FFDI) of a site over a period of years (Lucas et al, 2007). This cumulative monthly or seasonal FFDI can be used to compare fire weather parameters (including temperature, humidity, drought index) over the period of recorded weather data. The use of cumulative FFDI and prediction of climate change models is useful and indicative but does not of itself provide an adequate basis for establishing the limits of predictability for fire behaviour alone (Hennessey et al 2005). The cumulative FFDI is therefore a surrogate for observing the effects of climate change over the period of record (up to about 30 years) and has been used to suggest changes in fire season and potential changes in fire recurrence (Hennessey et al, 2005). At the international level, the Intergovernmental Panel on Climate Change (IPCC) met and agreed to its 4th Assessment Report at Valencia, Spain on 12-17 November 2007 (IPCC, 2007). This report was the culmination of 3 working groups and many years of research in the area of climate change.

The IPCC findings within the 4th Assessment Report are important in establishing possible future scenarios. For example, the report states "*Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level*". Annual average global temperatures have been increasing steadily over the last 130 years.

More recently, the IPCC has issued its 5th report, which confirms and extends concern for global warming and increased losses from natural hazards, including bushfires (IPCC, 2014).

The changing levels of greenhouse gases that contribute to climate change are expected to increase over the next few decades irrespective of action to reduce their emissions. When applied to various climate models the effects show a general trend in climatic variables, with increases in annual ∑FFDI and FFDI percentile values (Lucas, 2009). For Australia, mean annual temperatures are expected to rise by 1.0 °C (range 0.6 – 1.5 °C), a 2-5% decrease in rainfall and increase in number of dry days and a small decrease in relative humidity by 2030. The El Nino/Southern Oscillation (ENSO) frequency is not likely to alter, however associated westerlies may be weaker (AFAC 2009). Importantly, adverse fire weather conditions have been reported to be correlated to the ENSO events and the Indian Ocean Dipole, independently of climate change (Ummenhofer et al, 2009a).Crompton et al (2010) has normalised property and life losses accounting for population, income and inflation, and identified that the ENSO and positive IOD gave rise to losses rather than changes in climate change.

Increases in average temperature due to climate change may occur (Hasson et al, 2008) but do not directly indicate increased bushfire severity. Based on the McArthur bushfire behaviour model (Noble et al, 1980), it is difficult to determine whether or not the recurrence of EXTREME forest fire danger would differ significantly from the current range without a careful analysis of each variable climatic condition used to determine FFDI (Hennessey et al, 2007; Lucas et al, 2009; Clarke et al, 2011). This is especially true as wind speed (typically from the west/north-west), temperature and humidity are major ambient drivers of daily FFDI and drought is more a precursor (conditioning driver) to fire frequency rather than fire severity (Bradstock et al, 2009).

Further, it is crucial that in developing adaptive strategies in response to the inevitable consequences of climate change, the disaggregation of climate data to compare bushfire impacts needs to occur to determine existing and trend severity in addition to frequency of extreme events, recurrence or extended fire seasons.

In summary, climate change is almost certain to give rise to increased frequency of severe drought in south-east Australia and as such, increased frequency and prolonged period of adverse bushfire conditions. This may also extend the fire season from summer dominated to increasingly spring and autumn in south-east Australia. What is not yet clear is the effect that climate change will have on the severity of bushfire events, however, increased recurrence periods can be expected (Hennessey et al, 2005). These changes in fire frequency are not however sufficiently clear in developing the bushfire scenarios for future planning and adaptation strategies without an adequate disaggregation of climatic data and applying these to fire behaviour models. The role of various fire behaviour models and their requirements in determining the bushfire scenarios are discussed in the next chapter of this thesis.

1.5 Strategic Response to House Losses

Determining the severity of a potential bushfire for land-use planning and construction practice purposes is crucial in any planning assessment process (Douglas and Ellis, 2000). Property protection measures are related to the concept of a 'design bushfire' (Douglas, 2012) or flame configuration. Obtaining the correct inputs for developing the design bushfire is therefore critical in considering the protection of life and property assets, including resident and fire fighter safety, protection of homes and other infrastructure and the need to balance environmental objectives. Deterministic approaches to bushfire behaviour combined with fire engineering principles have been applied to determine defendable space for fire fighters and building protection in North America (Butler and Cohen, 1998; Gentle and Rice, 2002), in Portugal (Zárate al, 2008) and in Australia (Douglas and Tan, 2005) .

Bushfire risk can be used to consider the relative roles of fuel, ignition sources, building vulnerability and weather conditions (Bradstock et al, 1998) within the broader landscape. In the USA, computer simulations such as *Farsite*, which is fire spread simulator and uses topography, fuel weather and other information to enhance land management and operational decision-making (Finney, 2004). *Farsite* uses existing fire behaviour models used in the USA, however, is largely seen as a land management resource, rather than having land-use capability. Within Australia, some effort has been made to consider house loss prediction and land-use through the use of the *Phoenix Rapidfire* program, which is conceptually similar to *Farsite*, but utilizes Australian fire behaviour models (Tolhurst et al, 2014).

In bushfire engineering, the design bushfire is dependent on weather and topographical conditions as well as the predominant vegetation class (fuel loads or structure) over which the fire burns (Ramsay et al, 2006). In some cases designers may seek to develop alternate design bushfires (Ramsay et al, 2006) as weather conditions and vegetation may deviate from the presumed conditions used within the 'deemed to satisfy' provisions of the Australian building code (ABCB, 2014).

Attempts have been made in the past to quantify suitable design bushfires based on a frequency distribution profile of fire weather. Andrews et al (2003) considered the utilization of logistic regression and percentile analysis in describing severe weather. Blanchi et al (2010) compared bushfire statistics in Australia from 1957 to 2009 with local meteorological conditions to determine conditions under which house loss was likely. The concept of annual occurrence of exceedance (return period or recurrence) for FFDI is used by the New South Wales (NSW) Rural Fire Service as a major input for determining the design bushfire conditions where a performance approach is proposed (NSW RFS, 2006). In addition, there are significant differences in fuel loads of vegetation assumed by planning practice (RFS, 2006) and that are used in construction practice (AS3959, 2009).

The sensitivity of FFDI used to estimate fire danger throughout Australia has been considered by Williams et al (2001) and linked to increased recurrence of fires as measured in terms of VERY HIGH and EXTREME events and a significant relationship was found with maximum daily temperature.

A major difficulty therefore is in defining bushfire scenarios for design and assessment purposes. No two fire events are the same. The failure to obtain the appropriate design bushfire can result in additional costs to the environment or construction for land holders or alternatively, the failure of the building systems to withstand the likely fire event. For example, the environmental conditions for the Victorian bushfires in 1939 were deemed to have set the ‘benchmark’ of worst possible conditions for bushfires and the corresponding FFDI value was set at 100 to mark the presumed upper limit of the scale (Sullivan, 2004). However these conditions and the FFDI 100 limit were exceeded on many occasions. Table 1.1 provides a list of recent examples of such fire events and FFDI ratings. The exceedance of the benchmark FFDI value of 100 presents challenges as to what is the appropriate benchmark for design in bushfire prone areas and whether a unified benchmark value exists.

Table 1.1: Recent Australian major bushfire events exceeding FFDI 100

Event	Year	FFDI	Source
Ash Wednesday Vic.	1983	>100	Sullivan, 2004
Mt Hall fire NSW	2001	>100	NSW Rural Fire Service, 2002
ACT (Duffy, etc.)	2003	105	McLeod, 2003
Victoria's Black Saturday	2009	up to 185	Bureau of Meteorology, 2009

The overall impact of climate change is undertaken using global climatic modeling (GCM) to develop 'scenarios' arising from different emission patterns into the future, however such models are not suited for infrequent *extreme* events at the small scale (point source) due to their limited spatial and temporal resolution (Hasson et al, 2008).

These scenarios have potential to impact on policy direction on issues such as planning policy for future residential areas, the construction of buildings in bushfire prone areas, the levels of hazard reduction needed to mitigate against the severity of events and assist with managing fire events, and risk assessment of existing areas, to ascertain likely vulnerabilities and corrective measures (Bradstock, 2003).

To best describe these scenarios, it is necessary to ensure accurate measurement of the major variables giving rise to bushfire events, that is the effect of fuel, weather and topography within a given geographical setting. This is best undertaken using historical data, where available (Lucas, 2010).

Fuels are assessed using a variety of techniques, and the assessment process needs to be relevant to the fire behaviour models applied (Watson, 2009). The more recent alternate model developed in Project Vesta (Cheney et al, 2012) is believed to more accurately reflect rates of spread conditions in higher intensity fires than the McArthur Forest Fire Danger Meter, however the fuel assessment approach differs from McArthur approach as does the use of weather parameters in deriving fire behaviour including rates of spread and flame length.

The details of various fire behaviour models including the McArthur Fire Danger Meter 5 model (FFDM5) and the Project Vesta model (DEFFM) are discussed in Chapter 2.

1.6 Focus of Research

In the aftermath of the 1983 Ash Wednesday fires of Victoria and South Australia, much work had been undertaken to improve the resilience of communities facing major fire events (Ramsay et al, 1987). In January 1994 major fires occurred in Sydney, including the Como-Jannali fires. Extensive research on house losses by CSIRO led to major recommendations on construction (Ramsay and McArthur, 1995).

In NSW, the focus turned to improved land use planning (Dept. of Urban Affairs and Planning, 1989). The NSW Rural Fire Service (and its predecessors) acknowledged the relationship between land-use planning and construction with the release of *Planning for Bushfire Protection* (in 1991, 2001 and 2006). Early methodological approaches had relied on fire intensity as a surrogate for bushfire attack. In 2002, this methodological approach (of using fire intensity) changed to the determination of radiant heat and flame length as a measure of direct bushfire attack (RFS, 2001). In 2006, the methodology was further refined with the application of the 'view factor method' in determining radiant heat as an engineered solution (Douglas and Tan, 2005). Each of these approaches however, relied on the application of the McArthur Forest Fire Danger model (Noble et al, 1980) for forest fire behaviour (referred to as FFDM5). As indicated above the McArthur Forest Fire Danger Meter model(s) applies to lower intensity fires (including for hazard reduction) and may not be appropriate for higher intensity fires, especially in terms of forward rate of spread (McCaw et al, 2008). In each case, the application of fire weather data has been inferred rather than adequately assessed from past events (Douglas et al, 2014).

Vegetation assessment has been overly simplified across a range of vegetation classes without identifying or recognising regional differences in fuel load or structure. The conclusion of the Project Vesta experiments has provided an opportunity to review the current approaches and improve them based on an alternative analysis of fire weather data and actual forest fuel characteristics (Gould et al, 2007a). A comparison of past results with new data will provide a previously unknown set of conditions to be considered and applied to improve community safety in bushfire prone environments.

The major knowledge gap that has arisen is the true extent of future fire weather (or rather climate) and vegetation (fuel) on the potential for house losses for the purposes of land-use planning and construction. The problem is one of defining the design bushfire to be used at the regional level based on climatic and vegetation data under the influence of climatic change arising from anthropogenic sources of global atmospheric pollution.

In addition, the selection of the most suitable empirical fire behaviour models and their input parameters for determining such a design bushfire needs to be assessed.

1.7 Aim and Scope of the Current Study

The purposeof this study is to consider the implication of regional climatic variables under a pattern of climate change to bushfire weather and forest vegetation classes for use in the planning and construction of residential developments in bushfire prone areas. The study will focus on NSW as vegetation and weather data suitable for assessment can be applied to current land use planning and construction practice within that jurisdiction.

The aims of the study are:

1. To review predictive capability for bushfire behaviour, specifically by comparing two forest fire behaviour models (Ch 2 & 6);
2. To review the roles of vegetation and climate as influences on bushfire behaviour (Ch3 & 4);
3. To assess extreme fire weather indicators for NSW (Ch 5 & 6);
4. To define design bushfires for forest and woodland landscapes across climate regions of NSW (Ch 7);and
5. To determine the influence of climate cycles and climate change on fire weather incidence and examine implications for design bushfires (Ch 8).

The significance of the proposed study is to enable the community in bushfire prone areas to better prepare for adaptation to climate change (Bosomworth and Handmer, 2008). The impact of climate change as a determinant of future fire events, either in terms of seasonality, frequency and severity/intensity will be evaluated. Of particular concern is the issue of how climate change may affect fire intensities or if the ‘design bushfire’ will increase within an appropriate recurrence or return period.

The findings of the proposed study are important for the preparedness of communities and fire services in the following key areas:

- The identification of risk profiles based on current and projected climate *extremes* in association with vegetation and topography of landscapes affected by bushfire events;
- The establishment of benchmarks for an appropriate design bushfire that can be used in developing strategic planning profiles for emergency services in New South Wales;
- The provision of improved information for public policy in relation to land-use planning and construction of buildings in bushfire prone areas; and
- An improved methodology for considering the suitability of alternative strategies for community infrastructure and preparedness arrangements.

The hypotheses for study can be considered therefore in three ways based on recurrence of *extreme*fire weather events and the consequences of bushfires in terms of bushfire behaviour and potential house loss. The impacts of climate change must also be based on regional weather and vegetation/terrain (as well as people) and the interaction between them (Flannigan et al, 2009).

It is hypothesised that on current evidence:

- The changes in annual and seasonal fire weather is likely to be extended in New South Wales. If this occurs, there will be an increased period for bushfire in a given fire district each season (Clarke et al, 2012);
- *Extremes* of fire weather events will increase at a given recurrence period (1:50year) due to climate change;
- Design bushfires based on the McArthur (FFDM5) and Project Vesta (DEFFM) models will provide similar outcomes for land-use planning and construction in forested areas of New South Wales; and
- A more robust method can be used for selecting design bushfire scenarios with consideration of different fire weather parameters.

Should human induced climate change be apparent at the *extreme*, then it is expected that the current weather data should also give clues of future climate scenarios. This is important if communities are to develop adaptation strategies that can be identified and to establish an appropriate response in relation to climate change and supplement computer simulations.

1.8 Outcomes

The focus of this thesis are the effects climate change may have in either increased frequency of annual and seasonal bushfire weather, changes in seasonality to more severe events, and/or increases in recurrence of events at the *extreme*. For example, increased drought may increase the period of the burning season, but of itself may not increase bushfire intensity which is also dependent on other aspects of daily weather conditions (e.g. wind speed, humidity or temperature). Increased average temperatures may be derived from higher minimum temperature days rather than an increase in maximum temperatures. Increased bushfire intensity would need to be associated with increased winds, reduced humidity and/or increased temperatures (Pitman et al, 2007; Flannigan et al, 2009).

An additional aspect of this thesis is to consider the various inputs to rates of spread and flame height using Australian forest fire behaviour models and applying data relevant to NSW fire weather districts (and associated vegetation classes) so as to determine appropriate controls for land-use planning and construction of buildings in bushfire prone environments. To do this, the project will seek to obtain relevant weather data for these fire weather districts or areas (over approximately a 20-43 year period where available) from the Bureau of Meteorology.

The application of fuel data would enhance the focus of the project by allowing calculations of a derived design bushfire in conjunction with the determined climatic conditions of this project. It should be possible to apply this bushfire modelling to the outcomes of the current study's climatic work as inputs suitable for application in the Project Vesta equations and compare these to McArthur equation outcomes.

The outcomes of the study will include:

- A comparison of two Australian forest fire behaviour models (FFDM5 and DEFFM), fire weather and vegetation in the landscape of the various NSW fire weather districts as they relate to the bushfire problem (noting that forest and woodlands are not extant over the whole of the New South Wales landscape);

- Fuel characteristics of NSW forest and woodland vegetation classes for use in Australian fire behaviour models (FFDM5 and DEFFM) and applicable in suitable NSW fire weather districts;
- Recurrence/return periods for fire weather conditions (based on FFDI) for use in fire behaviour determinations (using FFDM5) in each NSW fire weather district;
- Changes in FFDI, fuel moisture conditions (FMC) and drought (KBDI) to describe annual and seasonal shifts; and the number of days exceeding thresholds for these parameters arising from changes in climate for NSW fire weather districts;
- A comparative assessment of fire behaviour (rates of spread and flame heights) of two fire behaviour models at the *extreme* (i.e. @1:50 year recurrence) and implications for land-use and construction practice;
- The determination of the appropriate 'design bushfire' for regional landscapes (fire weather districts) in NSW; and
- The changes in fire weather indices (FFDI, FMC and KBDI) arising from climate change and the influence of Southern Oscillation Index (SOI) on the design bushfire for NSW fire weather districts.

1.9 Overview of Methodological Approaches

A comprehensive literature review was conducted to establish and structure the theoretical framework that relates bushfire behaviour with all relevant contributing parameters including weather conditions and fuel. The current research involves statistical analysis of weather parameters to describe climate and climate change, improved statistical approaches for determining fire weather as an input to fire behaviour models; and the application of new data to current land use and construction practice.

1.10 Overview of the Thesis.

Chapter 2 presents the literature review on the characterisation of **bushfire behaviour**, its relationship to environmental conditions and its influence on the development of suitable bushfire design. The review focuses on fire behaviour models for forest and woodland vegetation, however, scrub and shrubland vegetation and grassland models are also considered. The role of radiant heat models used in the site assessment for AS 3959-2009 is also considered, based as it is on flame characteristics/dimensions.

In chapter 3, a literature review on **vegetation classification systems** and vegetation classes used in NSW and their respective fuel characteristics was assessed. Vegetation data as an input to fire behaviour models was derived from a study that was compiled for the NSW RFS by the University of Wollongong (Watson, 2009). The Watson (2009) study (and associated studies) reviewed all sources relating to fuel accumulation rates, however, the study has not been used to calculate average fuel characteristics in a comprehensive way. The current study will seek to not only confirm the distribution of NSW vegetation classes, but also the fuel characteristics in terms of fuel loads and fuel structure. These characteristics will form an underlying basis of comparison between the fire behaviour approaches of FFDM5 and DEFFM to flame geometry.

Chapter 4 provides a literature review on the current role of **fire weather,** data considerations and previous studies on climate change in Australia and NSW related to bushfire events. This chapter includes discussions on existing trends in fire weather including temperature, precipitation, wind speed and drought as well as observed changes in seasonal conditions. The discussion also covers longer term trends with a focus on ENSO and the Indian Ocean Dipole.

Chapter 5 considers the **data sources and detailed methodology** used in the current study as well as the difficulties and limitations of data availability. A consolidated fire weather dataset for each of the 21 NSW fire weather districts has been developed for use in the current study and will be described as well as derived data for fuel moisture required by DEFFM equations. Data collection involves the use of existing dataset for the derivation of fire weather parameters (FFDI, wind speed and drought indices), the characterisation of fuel in terms of fuel loads, fuel structure and fuel moisture. Weather data was acquired from the Bureau of Meteorology for the compilation and derivation of a suitable historical dataset. The methodological approaches are to:

a) determine the distribution and fuel characteristics for NSW forest vegetation (excluding rainforests) and grassy woodlands;

b) derive daily FFDI and fuel moisture components from weather stations for all fire weather areas in NSW as inputs to the two bushfire behaviour models under consideration;

c) determine the return periods or recurrence of fire weather conditions using annual and seasonal metrics as well as ‘*extreme* value’ statistical techniques of fire weather parameters (FFDI, FMC and KBDI) suitable for use in fire behaviour models for all NSW fire weather areas;

d) utilise the fire behaviour models to determine rates of spread and flame heights at the *extreme*; and

e) apply fire engineering principles to flame characteristics to derive radiant heat outcomes in line with Australian Standards (AS 3959-2009) methodology.

Chapter 6 will address the **findings** of the study for fire weather characteristics in NSW fire weather areas including FFDI, average wind speed, drought, maximum temperature and relative humidity, as well as fuel moisture for use in bushfire site assessment. To do this, the study will employ 'extreme value analysis techniques' (EVA) to existing and additional derived NSW fire weather data. The advantage of the *extreme* value techniques is that assessment can be based on derived FFDI data (as well as FMC and KBDI) for a locality which is used to represent conditions over a broader part of the landscape.

Chapter 7 applies the findings of the previous chapters to derive revised flame lengths and comparative assessments for planning and construction practice for NSW fire weather districts. A comparison of the **results** of two fire behaviour models (FFDM5 and DEFFM) used in the study is also presented.

Chapter 8 provides an **analysis** of fire weather data over time periods to determine if such data indicates any trends and/or limits arising from the effects of climate change on:

a) annual and seasonal frequency of fire weather parameters,
b) increases in the threshold exceedance of these parameters, and
c) the severity of fire weather (and behaviour)parameters at the *extreme*.

Finally, Chapter 9 **concludes on the findings** and the implications of the study results for land-use and construction practice in NSW bushfire prone areas. It will also make recommendations and identify future research for other issues not covered by the current study.

Overall, the contribution to the field of land-use planning, construction practice, fire management and land management more generally, is that this study is capable of quantify risk profiles across the NSW landscape in a manner which has not been available to date.

CHAPTER 2 - BUSHFIRE BEHAVIOUR AND BUSHFIRE PROTECTION

2.1 Overview

In this chapter, the influence of fuel and weather conditions and the capability of the associated deterministic models for bushfire behaviour which are used for construction practice and land use planning are reviewed. Bushfire behaviour has primarily been characterised by rates of spread, fire line intensity, flame length (or height), crowning and spotting potential and convective columns and fire whirls (Potter and Werth, 2011). For the current study, the determination of flame characteristics (flame height) and rates of spread are central to radiant heat impacts and flame configuration when considering land use planning and construction practice. The determination of spotting potential and convective columns and whirls are beyond the scope of this study.

Bushfire behaviour models underpin the site assessment and construction measures used in bushfire prone areas and are sensitive to the underlying assumptions made as inputs to these models for the development of bushfire attack levels under the Australian Building Code of Australia (AS3959-2009) and defendable space. In essence these assumptions relate to weather, vegetation and slope (Douglas and Tan, 2005).

The key bushfire behaviour models which are or could potentially be used in construction practice under the Building Code of Australia (BCA)and in relation to land-use planning controls are discussed below. Chapter 3 considers the role of vegetation classes in NSW as an expression of fuel characteristics for use within these bushfire behaviour models. Chapter 4 considers the role of weather and climate of NSW and reviews the current state of knowledge relevant to developing improved fire weather inputs for bushfire protection.

2.2 Relevance of Bushfire Behaviour to Construction Practice

2.2.1 The Building Code of Australia and AS 3959-2009

The Building Code of Australia (BCA) (ABCB, 2016) is a uniform set of technical provisions for the design and construction of buildings and other structures throughout Australia. The BCA is a fully performance-based code and the stated 'performance requirements' are the only requirements which a building solution need to comply with(ABCB, 2016). The compliance of the performance requirements can be realised through either Deemed-to-Satisfy (DTS) Provisions, which are prescriptive in nature or Performance Solutions which can be developed using a verification method, testing or other suitable approaches.

The performance requirement for a Class 1 buildings in designated bushfire prone areas is set out in Volume 2 of the BCA which provides:

Performance Requirement - P2.3.4 Bushfire areas (ABCB, 2014).

A Class 1 building or a Class 10a building or deck associated with a Class 1 building that is constructed in a designated bushfire prone area must, to the degree necessary, be designed and constructed to reduce the risk of ignition from a bushfire, appropriate to the:

(a) Potential for ignition caused by burning embers, radiant heat or flame generated by a bushfire; and

(b) Intensity of the bushfire attack on the building.

When the DTS solutions are sought, the Standard AS 3959-2009 *Construction of Buildings in Bushfire Prone Areas* should be referred to as the suitable construction manual. Similar provisions relate to other classes of buildings, notably Classes 2, 3, 4 and special fire protection purposes in NSW.

The nature of construction practice is that it seeks to resolve issues at the site specific level, however, fire behaviour models operate at broader spatial scales. Of the three variables of weather, fuel and slope, it is only slope which can provide a truly site specific condition. Vegetation classification, by its very nature means that it is unlikely that site specific considerations will be accessible, hence there will be a reliance on higher order classes to represent relevant fuel conditions. Weather conditions operate at the broader regional scale (Lucas, 2010). although differences may occur over short distances which may be associated with aspect, local water bodies or topographical features.

2.2.2 Australian Standard AS 3959-2009

In NSW, the residential development of buildings of Classes 1, 2, 3 and 4 and those buildings which are a 'Special Fire Protection Purpose' (mostly class 9 buildings) in designated bushfire prone areas need to comply with Building Code of Australia and AS 3959 -2009 (Standards Australia, 2009) which incorporates a site assessment methodology. The purpose of the site assessment is to determine the category of bush fire attack (BAL) and the level of construction required to compensate for this bushfire attack.

Section 1 of the Australian Standard deals with the objectives and scope and provides definitions for use within the Standard (Standards Australia, 2009). This includes Bushfire Attack Level or BAL which is defined as "*A means of measuring the severity of a building's potential exposure to ember attack, radiant heat and direct flame contact, using increments of radiant heat expressed in kilowatts per metre squared, and the basis for establishing the requirements for construction to improve protection of building elements from attack by bushfire.*"

Table 2.1 illustrates the relevant BAL levels adopted by the Australian Standard AS 3959-2009 and the relevant bushfire exposure and predicted bushfire attack mechanisms.

Table2.1: Bushfire Attack Levels and corresponding exposure thresholds for construction practice (Source:AS3959, 2009)

Bushfire Attack Level (BAL)	Radiant heat flux exposure thresholds	Description of predicted bushfire attack and levels of exposure.
BAL – Low	Generally greater than 100 m from classified vegetation (>50 m for grasslands).	There is insufficient risk to warrant specific construction requirements.
BAL – 12.5	$\leq$12.5 kW/m^2	Ember attack
BAL – 19	>12.5 kW/m^2 and $\leq$19 kW/m^2	Increasing levels of ember attack and burning debris ignited by windborne embers together with increasing radiant heat flux.
BAL – 29	>19 kW/m^2 and $\leq$29 KW/m^2	Increasing levels of ember attack and burning debris ignited by windborne embers together with increasing radiant heat flux.
BAL – 40	>29 kW/m^2 and $\leq$40kW/m^2	Increasing levels of ember attack and burning debris ignited by windborne embers together with increasing radiant heat flux with the increased likelihood of exposure to flames.
BAL – Flame Zone	>40kW/m^2	Direct exposure to flames from fire front in addition to heat flux and ember attack.

The basic model for determining radiant heat and construction performance is illustrated below (taken from Douglas and Tan, 2005) in Figure 2.1. As can be seen inputs are required for fire weather, fuel and slope which could also need to be adjusted for the DEFFM equations as the current approach utilises the FFDM5 equations (Noble et al, 1980).

In 2015, the ABCB also proposed a (draft) verification method, which sought to introduce a recurrence level when developing the design conditions for a performance approach to buildings in bushfire prone areas.

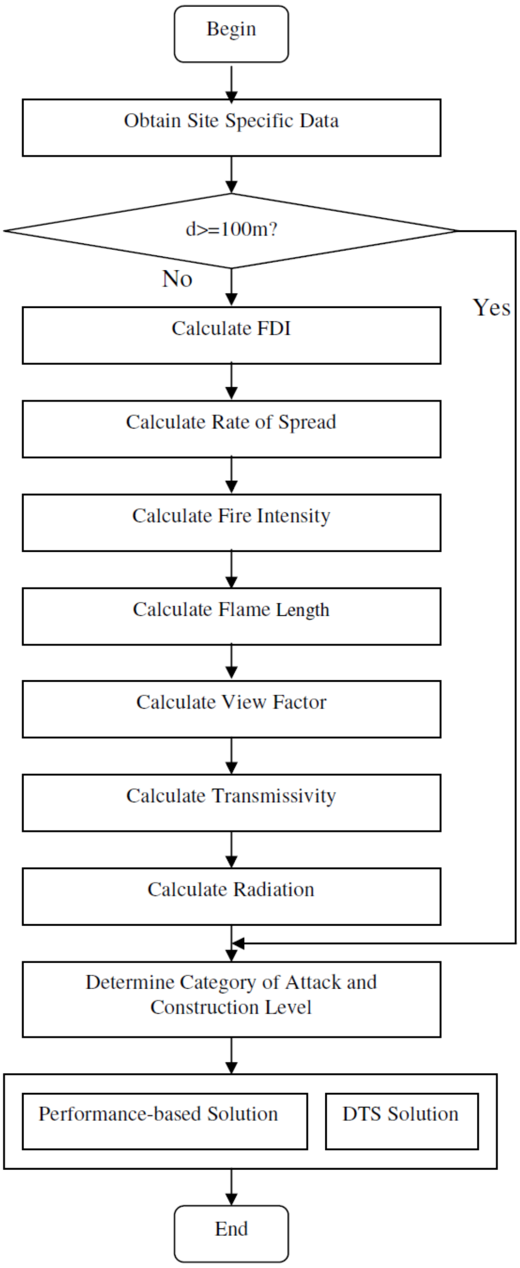


Figure 2.1: Model for determining radiant heat and construction (Source: Douglas and Tan, 2005)

Depending on the calculated BAL, AS 3959 (2009) requires specific construction requirements which are resilient to increasingly higher radiation heat exposures.

Understanding bushfire behaviour is therefore crucial not only for operational aspects and fire fighter safety during major fire events (Sullivan, 2009) but also for the determination of safety distances for the protection of houses from flame contact, radiant heat and embers (Butler and Cohen, 1998).

A review of mathematical models of fire behaviour has identified three main approaches being; theoretical models, empirical models and semi-empirical (quasi-physical) models which are used for predicting surface fire spread, crown fire, spotting and ground fires (Sullivan, 2009a). Importantly these models can be used to estimate wildfire spread or geometric flame front characteristics (Pastor et al, 2003). Many of these models though are dependent on fuel and weather conditions at the landscape level and can vary significantly locally (Cruz and Gould, 2009).

A bushfire will spread in either two dimensional or three dimensional ways (Perry, 1988). The latter includes the vertical spread into the crown (Alexander and Cruz, 2006). Rates of spread may vary depending on prevailing winds and slopes (Viegas, 2004; Weise and Biging, 1996) and can form head fires, backing fire and flank fires as illustrated in Figure 2.2.

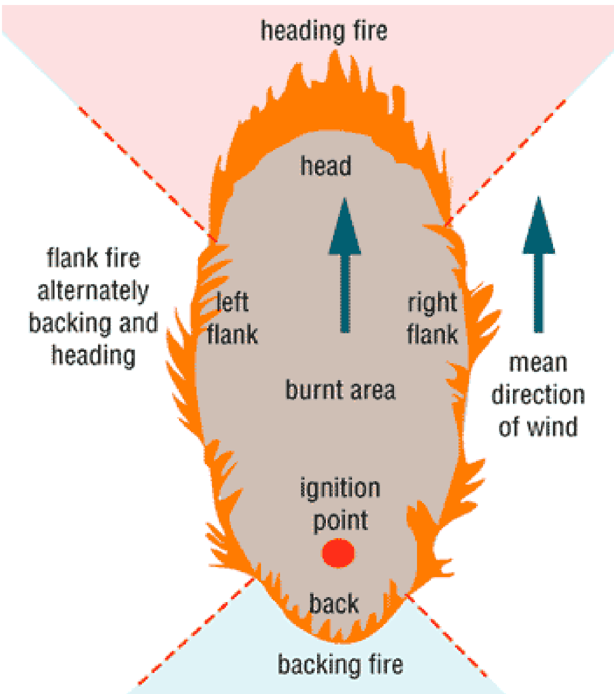


Figure 2.2: Parts of a moving fire showing head fire, flank fire and backing fire. (Source: Cheney and Sullivan, 2008)

Importantly, some models refer to flame length whereas others refer to flame height (i.e. the flame length titled arising from wind or slope effects) (Cheney and Sullivan, 2008).

There are three broad classes of bushfire behaviour models used for land-use planning and construction practice in Australia:

- Forest fire behaviour models, including McArthur's Forest Fire Danger Meter Mark 5 (FFDM5) model, and the Project Vesta (DEFFM) model;
- Shrubland models; and
- Grassland models including the McArthur grassland model and the CSIRO Northern Australian Grassland meter (Cruz et al, 2015).

Initial efforts in Australia at determining appropriate bushfire protection measures for land-use relied on empirical fire line intensity models to describe fire behaviour and impact on land-use planning (Department of Planning, 1989). This contrasted with more recent attempts which developed more sophisticated approaches based on radiant heat impacts on receivers (Ellis, 2000 and Douglas and Tan, 2005) derived from rate of spread and flame height. These aspects of fire behaviour (that is forward rate of spread and flame height) constitutes a significant part of the current project and its application to different forest classes across New South Wales. Although some work has commenced in relation to convective columns and fire generated or fire enhanced wind events (Douglas et al, 2010; He et al, 2011), this has not been translated into an adopted methodology for assessing building protection.

A model used for meeting the performance requirements of the Building Code of Australia has been proposed for the impacts of bushfire radiant heat and flame contact on buildings in bushfire prone areas (Douglas et al, 2006). More recently, the ABCB has proposed a draft verification method incorporating return periods and failure rates for meeting the bushfire requirements of the BCA (ABCB, 2014). The choice of models is crucial in developing a consistent, robust and reliable assessment method which must quantify for different vegetation classes (or types), the parameters of bushfire attack (principally flame length and radiant heat) that can result in house losses and/or damage (Douglas and Ellis, 2000). This approach currently utilises McArthur's Forest Fire Danger Index system with standardised fuel load data for all forests, woodlands and rainforests as deemed to satisfy inputs (Standards Australia, 2009).

The two key models for fire behaviour to be considered for forest fire in Australia are those of FFDM5 using Forest Fire Danger Index (FFDI)(Noble et al, 1980; Sirakoff, 1985) and DEFFM (Cheney et al, 2012). These and other bushfire behaviour models are described below.

FFDI has been recognized as most predictive of forest fire behavior including rate of spread at lower intensities though recent research suggests FFDI under predicts rates of spread at the higher range of FFDI (Dowdy et al, 2009). In particular, the FFDI value of 12 is often used as a threshold below which hazard reduction burnings can be prescribed with safety (RFS, 2002a), although Lucas et al (2007) suggests that FFDI>25 reflects fire season conditions.

The more recent DEFFM model developed is believed to more accurately reflect rates of spread conditions in higher intensity fires (McCaw et al, 2008), however the fuel assessment approach differs from FFDM5 approach as does the use of weather parameters in deriving fire behaviour including rates of spread and flame length (Cruz et al, 2015).

The application of fire weather data for planning and construction practice has been inferred rather than adequately assessed from past events and relied on assumed FFDI values. In some cases these have been supported by subsequent work although only indirectly (Hennessey et al, 2005).

In the past, the common approaches of fire authorities has been to consider the limited weather data available for a district and determine whether the policy decision for construction practice should be based on either the:

a) FFDI being exceeded on more than one occasion over the recent record available (about 30 years), which is assumed as the 1:50 year event (RFS, 2006);

b) FFDI corresponding to a prescribed cumulative frequency percentile value of an available dataset (Andrews et al, 2003); or

c) derived FFDI from maximum values of wind speed, temperature, drought factor and minimum relative humidity for EXTREME or CATASTROPHIC Summer data (Adrian, 2009).

The above approaches have been used by AS3959-2009 based on advice from the various State fire authorities. Each of these methods has significant shortfalls and does not represent a robust approach to the assessment of fire weather. The first approach is based on limited recorded event data and observed FFDI within those events and applied across the broader landscape. It is difficult to apply these event based fire weather conditions across multiple fire weather areas. The second approach is also limited by a dataset which may not be long enough to include *extreme* observations. The final approach may provide a maximum potential but may result in unrealistic and excessively high design criteria since it is highly unlikely that all contributing parameters to FFDI could attain the worst case values (so far as the FFDI is concerned) simultaneously at a given location.

These approaches have been used in the absence of a clear methodological and statistically appropriate approach to the determination of *extreme* events. It is also relevant to note that at the time of development of FFDI for planning and construction practice in NSW in 2005, the national fire weather dataset was not available to the fire services. These issues are explored further in Chapter 4.

2.3 Forest Fire Behaviour Models

Early work on fire behaviour prediction began in the 1960s with the publications by Rothermel and Albini in the USA (Anderson, 1982; Gould, 1991) and McArthur in Australia (Luke and McArthur, 1978). In the Australian context, two major models have been used largely for forest fire behaviour purposes. The first model was developed as a nomogram by the CSIRO (McArthur, 1978), which were subsequently incorporated into a circular meter (e.g. FFDM5).The second model occurred in Western Australia with the development of the Forest Department's *Forest Fire Behaviour Tables* (FFBT) developed by Peet in 1965 (Gould et al, 2007; McCaw et al, 2012). In the absence of other empirical data, both of these models where extrapolated beyond the original intended use oflower intensity fires (Cheney et al, 2012; McCaw et al, 2008).

USA models have not been used operationally in Australia (Gould, 1991). In the USA, fire behaviour models have been used by the major national and State land management agencies (Scott and Burgen, 2005) and have been developed into sophisticated computer simulations (Farsite) for considering impacts on communities, notably within the Wildland Urban Interface (Finney, 2014).

More recently, experimental fires in Western Australia have led to the development of the Dry Eucalypt Forest Fire Model (DEFFM) also known by the name Project Vesta. The

FFDM5, FFBT and DEFFM and other Australian fire behaviour models are discussed in more detail below.

2.3.1McArthur fire behaviour model (FFDM5)

The principle indicator of bushfire weather (danger) has been the use of a non-dimensional index referred to as the Forest (and Grassland) Fire Danger Index or FFDI (and GFDI) and its related forest (or grassland) fire danger ratings (see Figure 2.3).

The FFDI generally describes the chances of a fire spreading (for a given ignition condition), fire behaviour and difficulty in suppression (Verdon et al, 2004; CSIRO, 2009; and Standards Australia, 2009). FFDI can be used to determine both rates of spread and flame length, although experimental fires in the late 1990s suggested that rates of spread could be three times that predicted by the existing models for higher fire weather conditions and with line fires (Gould et al, 2007a). These differences are felt to be related to the experimental design of the earlier experiments and the stage at which these fires had developed. The experimental fires in ACT and WA were ranked as low intensity fires and had not reached quasi-steady state conditions due to limited fire line widths (McCaw et al, 2008) before being extinguished.

McArthur's forest fire danger index (and rating) system is mathematically formulated by Noble et al (1980) and is presented as the exponential function below.

$$F = 2.0\exp(-0.450 + 0.987\ \ln(D) - 0.0345RH + 0.0338T + 0.0234U_{10}) \qquad (2.1)$$

where:

F = FFDI;

D = drought factor;

RH = relative humidity (%);

U_{10} = wind speed at 10 m above ground (kph); and

T = air temperature(°C).

It can be seen that the exponential function can give rise to dramatically increased indices with smaller changes in relative humidity or wind speed and/or temperature. The sensitivity of FFDI to each input parameter determines the importance of that parameter and the long term implications arising from changes in climatic conditions (Dowdy et al, 2009). Clearly from Eq. 2.2FFDI is most sensitive to drought factor (D). Relative humidity, temperature and wind share similar sensitivity and hence almost equal importance in determining the value of fire danger index. It is worthwhile noting that both drought factor and relative humidity are correlated with temperature (Dowdy et al, 2009).

The Drought Factor (*D*) is given by Noble et al (1980) as:

$$D = \max\left\{> 1, \min\left[10, \frac{0.191\ (KBDI\ +\ 104)\ (N + 1)1.5}{3.52\ (N\ +\ 1)1.5\ +\ P -\ 1]\}}\right]\right\} \tag{2.2}$$

where:

KBDI = the daily Keetch-ByramDrought Index (mm);

P = daily precipitation (in mm);

N = number of days since rain.

Equation (2.2) artificially sets the range of D in [1, 10]. If the maximum value by the expression is greater than 10, then the value of D is set equal to 10. Likewise, if expression the expression yields a value of less than 1, D is set to 1.

The daily Keetch - Byram Drought Index (KBDI) represents the cumulative moisture deficit capacity of the soil and is calculated using maximum temperature (as a measure of evapo-transpiration) and effective daily rainfall (Luke and McArthur, 1978) with a maximum value of 200 mm for Australia, which represents a 200 mm soil saturation depth (Noble et al, 1980). Traditionally, the calculation of KBDI is undertaken by using a series of tables (Keetch and Byram, 1968); however these are now automated by the Bureau of Meteorology in conjunction with other similar drought indices (e.g. Mount SDI).

Effective precipitation is derived by deducting the first 5mm of precipitation which is assumed to be held by the canopy.

In effect

$$KBDIi = KBDI\text{i-1} + Et - Peff \tag{2.3}$$

where;

KBDIi = current days KBDI;

KBDIi-1 = KBDI of the previous day;

Et = evapo-transpiration (mm); and

Peff = effective precipitation (mm).

The drought factor and KBDI is calculated daily by the Bureau of Meteorology and is publicly available. In practice, KBDI would rarely reach a value of 200mm which would represent the worst possible drought. A threshold value of 150mm can be used to describe conditions where intense fire behaviour can be expected and suppression is not feasible (Melton, 1989), with the worst conditions exceeding 175mm.

In some jurisdictions (notably Tasmania), the FFDI is determined using Mount’s SDI, which is also a measure of soil moisture deficit. In NSW, KBDI not SDI is used for determining drought factor (Joint Fire Agencies, 1997).

It is interesting to note that the initial range of FFDI was arbitrarily set up to 100 based on the worst recorded weather condition at the time when the system was developed. These indices are also expressed as ratings (forest fire danger ratings) for community education and fire danger awareness.

In the light of the Victorian Black Saturday fires in February 2009; fire agencies across Australia have modified the Forest Fire Danger Ratings originally developed by Luke and McArthur (1978) in recognition of the concerns related to the public’s perception of bushfire events. The associated FFDI now exceeds the previous 1-100 numerical range and includes new categories for Severe and Catastrophic conditions. In practice, whole integers rather than fractional numbering are used (NSW RFS, 2009).

The current Forest Fire Danger Ratings system is illustrated in Table 2.2 and Figure 2.3.

Table 2.2: Current Forest Fire Danger Rating system (RFS, 2009)

Rating	LOW - MEDIUM	HIGH	VERY HIGH	SEVERE	EXTREME	CATASTROPHIC
FFDI range	**1-11**	**12-24**	**25-49**	**50-74**	**75-99**	**100+**

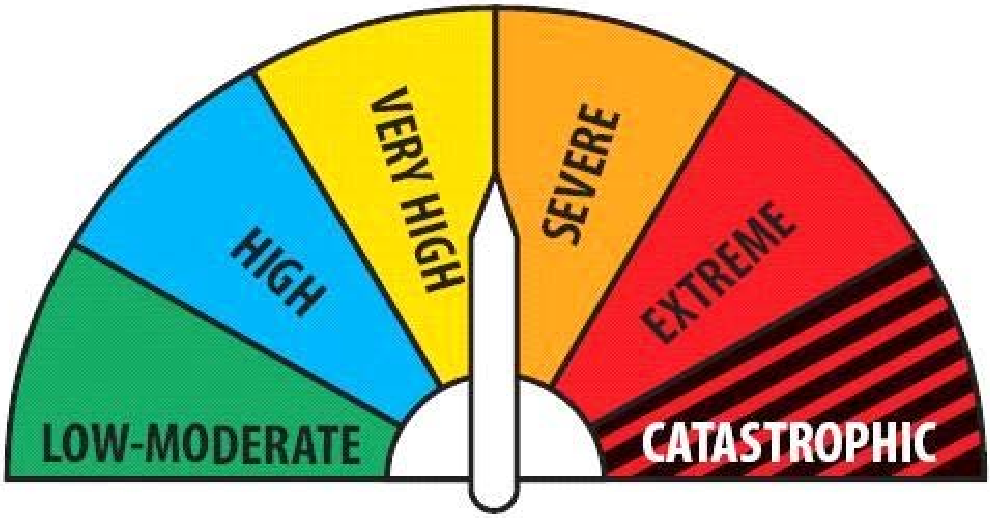


Figure 2.3: Current Fire Danger Ratings for NSW community education and fire awareness

In Australia, the use of FFDI has been recognised as most predictive of fire behaviour at lower intensities and in particular for use in prescribed burning but as discussed above under predicts rates of spread notably at higher FFDI's (Gould et al, 2007a; McCaw, 2008). In other vegetation classes such as heaths and shrub, rate of spread is determined by vegetation height and importantly wind speed alone. Grassland fire behaviour can be determined by the Grassland Fire Danger Index or GFDI (Noble et al, 1980) to describe fire weather conditions or by using wind speed only model(Cheney et al, 1998). These are briefly discussed in section 2.5 below.

There are various versions of the Forest Fire Danger Meter upon which the model and index is based. The current Mark 5 version of the Forest Fire Danger Meter has been extensively used in the context of S.E Australia (Lucas, 2010) and hence a reference to FFDI should be considered as arising from the Mark V meter (or FFDM5) described by Noble et al (1980).

For forest fires the forward rate of spread can be determined by the following equation (Noble et al, 1980):

$$Rm = 0.0012FW * \exp(0.069\theta) \qquad (2.4)$$

where

F = FFDI

W = fuel weight (t/Ha).

θ = slope in degrees ($-10^0 \leq \theta \leq 20^0$), and

Rm = rate of forward spread (kph) (for FFDM5).

Flame height is a crucial factor in determining radiant heat from fires (Douglas and Tan, 2005). Flame height (*Zm*) is related to rate of spread and weight of fuel and is determined using the equation (Noble et al, 1980):

$$Zm = (13.0*R + 0.24*W) - 2.0 \qquad (2.5)$$

where*Zm* is in metres (FFDM5).

To allow for discontinuities within flames (flame flashes) and other shielding effects arising from vegetation, the flame height is adjusted by approximately 50% to provide a sustained flame height (*Zma*) by dividing Eq. (2.5) by 2 (AS5939, 2009; Pastor et al, 2003; Ellis, 2005), and discounting the resultant 1, to yield equation (2.6):

$$Zma = (13.0*R + 0.24*W)/2 \qquad (2.6)$$

A flowchart of the FFDM5 model is shown in Figure 2.4. In effect this flowchart comprises inputs, intermediary and output parameters.

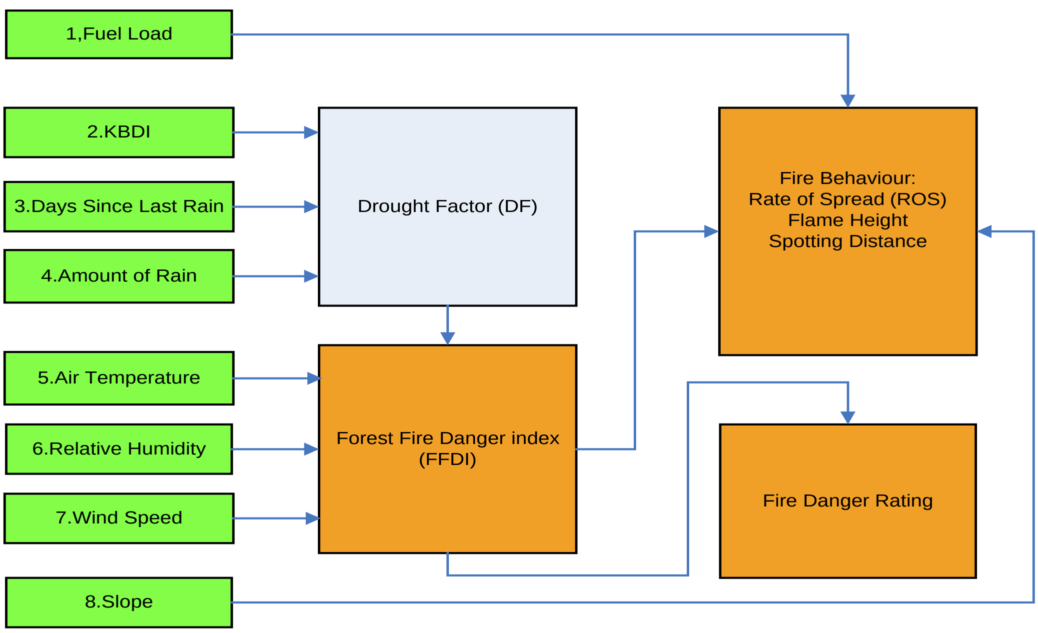


Figure 2.4: Flowchart of McArthur Forest Fire Danger Meter Mark 5 Fire Behaviour Model (FFDM5)

2.3.2Project Vesta model (DEFFM)

In 1996, the CSIRO in collaboration with the Western Australian Department of Environment and Conservation and supported by fire agencies across Australasia, initiated a project to review fire behaviour and spread of high intensity bushfires (Gould et al, 2007). The aims of the study were:

- To quantify the changes in the behaviour of fire in dry eucalypt forest as fuel develops with age;
- To characterise wind speed profiles in forest with different over storey vegetation and structure in relation to fire behaviour;
- To develop new algorithms describing the relationship between fire spread and wind speed, and fire spread and fuel characteristics including load, structure and height; and
- To develop a National Fire Behaviour Prediction System for dry eucalypt forest..

The major research outcome of Project Vesta (Dry Eucalypt Forest Fire Model or DEFFM) is the significant shift in predicted forward rate of spread based on fuel load estimates (and structure), wind speed, fuel moisture (and its relationship to drought) and slope. This research project also gave rise to revised flame height calculation. These revised rate of spread and flame height equations can be used for the determination of radiant heat at distances from the flame front. The subscript *'v'* is assigned to the DEFFM model for these outputs.

Key results of DEFFM (Gould et al 2007) include:

- "Numerical values of fuel structure (i.e. hazard score) correlate with fire spread and flame height and the hazard scoring system can be used to provide inputs for predicting fire behaviour……";
- Rate of spread is directly related to characteristics of fuel bed and understorey and the near-surface fuel is the principal layer for determining rate of spread; and
- A model has been developed to predict flame height from rate of spread and elevated fuel height

According to the DEFFM model flame height is determined by forward rate of spread (*Rv*) and elevated fuel height (E_{fn} in metres) in the following equations:

$$Rv = 30 + 3.102(U_{10} - U_t)^{0.904}\exp(0.279S_{fhs} + 0.611NS_{fhs} + 0.013NS_h) \quad (2.7)$$

and

$$Zv = 0.0193Rv^{0.723}\exp(0.64E_{fn}) \quad (2.8)$$

where

Rv = rate of spread (m/hr) at 0^{o} slope and 7% fuel moisture content (FMC).

U_t = threshold wind speed of 5 km/hr.

S_{fhs} = surface fuel hazard score,

NS_{fhs} = near-surface fuel hazard score,

NS_h = near-surface fuel height (cm).

If FMC is not equal to 7%, then fuel moisture is adjusted with the fuel moisture function *Mf* described in section 2.6.2 below.

Hazard scores are determined from photo-comparative guidelines which also provide associated fuel hazard ratings and structural fuel loads (Hines et al, 2010; Gould et al, 2007a). Further review on hazard score and hazard rating methods are given in Section 3.4.3 of this thesis.

In verifying the findings of DEFFM, it was found that a bias adjustment factor (*B*) for rate of spread and for flame height, gave improved correlation in addition to some changes to the rate of spread equation (Eq2.7) (Cheney et al, 2012). As a result, the above equations (Eqs 2.7 and 2.8) have been replaced (for a 5 kph threshold wind speed) by equations 2.9 and 2.10 (including fuel moisture adjustment) as follows:

$$Rv = \begin{cases} [30 + 1.5308(U_{10} - U_{\mathrm{t}})^{0.8576} FHSs^{0.9301}(FHSns.Hns)^{0.637}.Br]Mf & \text{for } U_{10} > U_{\mathrm{t}} \\ 30Mf & \text{for } U_{10} \leq U_{\mathrm{t}} \end{cases} \quad (2.9)$$

$$Zv = 0.0193Rv^{0.723}\exp(0.64He)Bf \quad (2.10)$$

where

FHS = Fuel Hazard Score with subscripts s=surface, ns=near surface,

Hns = height of near surface fuel (cm),

He = height of elevated fuel (cm),

Br = bias adjustment factor for ROS (= 1.03), and

Bf = bias adjustment factor for flame heights (=1.07).

Clearly fuel measurement is critical to the outcome of such an approach including hazard score and fuel height. Note also that rate of spread in (equation 2.9) is determined by wind speed and fuel structure, not FFDI as applies in the FFDM5 equations. So as to use the two forest fire behaviour models described above (i.e. FFDM5 and DEFFM) for rate of spread and flame height, it will be necessary to investigate fuel loads for the FFDM5 model, and fuel structure expressed as hazard scores and/or ratings with fuel moisture adjustment for DEFFM model (Gould et al, 2011). In addition, the two models require different fire weather inputs. The FFDM5 model rely on the forest fire danger index which incorporate a set of weather data including wind speed as explained in Eq.(2.1).

The DEFFM model uses wind speed only. In effect fuel moisture is incorporated with FFDI, but is an adjustment factors for DEFFM (see 2.6 below). It has been assumed that the forest fire behaviour models of FFDM5 and DEFFM will also apply to temperate woodlands (Douglas and Tan, 2005) due to structural similarities in vegetation.

There is little research of their applicability in relation to rainforests. Other models also apply to semi-arid woodlands and savannah woodlands (Cheney and Sullivan, 2008).

The flowchart for the DEFFM model is shown in Figure 2.5.

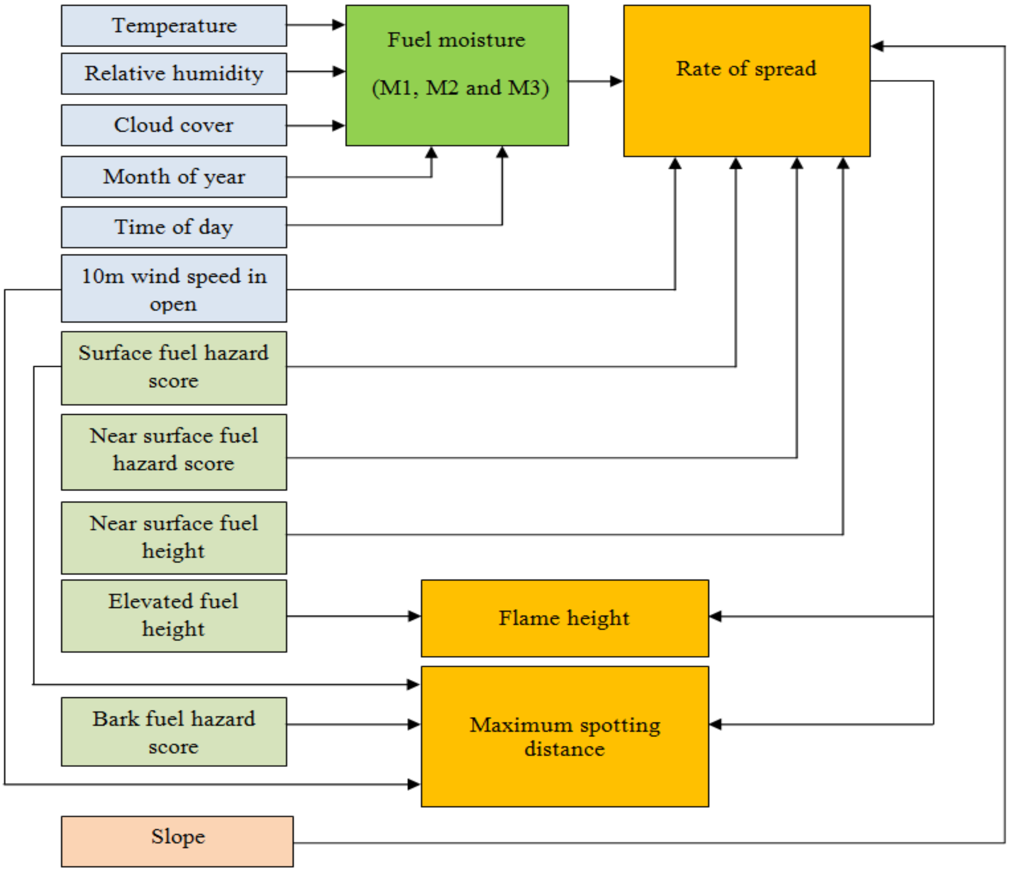


Figure 2.5 Flowchart for the Dry Eucalypt Forest Fire Behaviour Model(DEFFM)

Note that some of the inputs and the intermediary parameters vary from the FFDM5 above. M1, M2 and M3 refer to the fuel moisture equations in section 2.6.2.

2.3.3 Western Australia Forest Fire Behaviour Tables (FFBT)

The WA Forest Fire Behaviour Tables (or FFBT) was developed for both northern jarrah forests as well as the karri forests of WA (Sneeuwjagt and Peet, 1985). The former is often referred to in the context of prescribed burning (Cruz et al, 2015a) whereas the later is considered suitable for wet sclerophyll forests wildfires.

Under the FFBT, four variables influence the rate of spread being moisture content of surface litter (*MC*), fuel load (tpHa), in-forest wind speed ($U_{1.5}$), and slope (Beck, 1995). The fire danger index for Karri (FDI_k) is calculated from fuel moisture and in-forest wind speed (Cruz et al, 2015) by:

$$FDI_k = Y_k + A_k \exp(U_{1.5} N_k) \qquad (2.11)$$

where

FDI_k = fire danger index (for karri forest) (2.12)

$$Y_k = 4{,}88\text{-}263.78\ MC^{-1.8} \quad (2.13)$$

$$A_k = 163.40\ MC^{-1.18} \quad (2.14)$$

$$N_k = 0.54\text{-}0.0059MC \quad (2.15)$$

The forward rate of spread (*Rwa*, m/h) is the calculated using:

$$Rwa = FQCF_k FDI_k \quad (2.16)$$

where the 'fuel quantity correction factor' FQCFk is calculated for moisture content (of surface layer - i.e. *MC*) and available fuel (Cruz et al, 2015a).

Burrows and Sneeuwjagt (1991) describe the limitations of both the FFDM5 and FFBT approaches, including issues around fuel assessment and weather. Cruz et al (2015) indicate that the FFBT model should only be used for prescribed burning and that the DEFFM (Cheney et al, 2012) supersedes both the FFDM5 and FFBT models. On this basis, and because no NSW forests can be directly related to karri or jarrah (from WA), the use of the FFBT has not been pursued with the current study. However, this could be an area of future research.

2.4 Shrubland (Scrub) Fire Behaviour Models

Shrublands and scrub (tall heath) form a significant part of the Australian landscape and include the coastal heaths as well as the mallee shrublands of Far Western NSW. The distinction between shrublands and scrub arises from Australian vegetation classification systems (Specht 1970). In the Australian standard for construction in bushfire prone areas, these vegetation classes are distinguished by the vegetation height, with 2 metres forming the cut-off between shrubland and scrub (AS3959, 1999). These classes of vegetation are discussed in Chapter 3 in more detail.

Fires on shrubland do not follow either the FFDM5 model or DEFFM model for rate of spread or flame height. Laboratory and field experiments have provided some understanding of fire behaviour for shrubland, notably rates of spread. Factors which influence fire behaviour in Portuguese shrublands include wind speed, fuel moisture and fuel structure (height) (Fernandes, 2001). Early work was reported by Catchpole et al (1998) for Australian shrublands and scrubs more recently Anderson et al (2015) (see also

Cruz et al, 2012 and Cruz et al, 2015). One significant factor for shrublands may be related to the fuel moisture of the standing vegetation, which during periods of drought or other water deficit provides favourable condition for the initiation and propagation of fire through the canopy (Plucinski et al, 2010) rather than surface fuel loads in forests (Keeley, 2002).

Experimental fire data across Australasia, including New Zealand Manuka/Kanuka vegetation and button-grass moorland in Tasmania, were used to derive rate of spread equations at 2 m heights for wind speed (Anderson et al, 2015). These rate of spread *R* (kph)calculations need to be adjusted for 10 m wind speeds and slope (Tan et al, 2006; Standards Australia, 2009) using a mathematical variation of the above form developed by Catchpole et al (1998):

$$R=0.023U_{10}^{1.21}\,Hs^{0.54} \tag{2.17}$$

where

Hs = shrubland vegetation height (m).

Equation (2.11) shows that rate of spread over shrubland is less dependent on weather than forest as expressed through FFDI or in DEFFM (Equation 2.9). Wind speed is the sole influential weather factor. On the other hand, the FFDM5 model shows the explicit and more comprehensive weather dependence. The slope factor described by Noble et al (1980) and Gould et al (2007) can be applied to Equation 2.11 for slopes greater than or less than zero (flat ground). These issues are further discussed in 2.6.2 below.

There are no specific flame height calculations for shrublands and scrub in Australia, the relationship between fire line intensity and flame length of Byram's (1959) equation was used in Portugal (Fernandes, 2001) and Australia (Tan et al, 2006). Byram's(1959) equation is more likely to under-estimate flame height and the best fit for Australian shrublands is given by equation 2.18 below (Anderson, 2015).

$$Z = 0.0325\,I_b^{0.56} \tag{2.18}$$

whereI_b (in kW/m) is the fire line intensity described by Byram (1959).

In the mallee-heath communities of far Western NSW, recent work has attempted to link fire line intensity with flame height (Cruz et al, 2012) with reasonable accuracy and little bias. Although the present study is to examine forest fire protection, it should be possible to also derive suitable wind speeds for application with shrubland and scrub.

2.5 Grassland Fire Behaviour Models

The current study is mainly focussed on forest and woodland fires and is less concerned with grassland fires. However, it is useful to consider grassland fires as there are issues related to grassy woodlands where it has been advocated that the Northern Grasslands Fire Meter is appropriate for fire behaviour, notably rates of spread, determination (Cheney and Sullivan, 2008).

Unlike shrubland and scrub (or mallee), the fire behaviour of grasslands have had a longer history of assessment and investigation by fire researchers and fire authorities (Cheney and Sullivan, 2008). These experimental investigations have led to the development of a number of models (or their versions), largely by the CSIRO (Noble et al, 1980; Cheney and Sullivan, 2008; and Purton, 1982). The adopted model by Australian Standard AS 3959 is the 1997 CSIRO Grasslands Fire Danger Meter Mark 4 (Cheney and Sullivan, 2008).

As with the forest fire danger meter, the 1997 *Mark 4Grassland Fire Danger Meter* is a deterministic approach and empirical model that relies on the calculation of a grassland fire danger index or GFDI (as opposed to the forest fire danger index or FFDI). GFDI is uncapped but normally ranges from 1-200 (on the meter). The subsequent (CSIRO modified) *Mark 5Grassland Fire Danger Meter* is generally a metrification of the earlier *McArthur Grassland Fire Danger Meter* (Luke and McArthur, 1978), although Purton (1982) notes that there has been some additional adjustment by McArthur which does not allow direct conversion. In addition to wind speed, humidity and air temperature, this model uses grassland curing to determine GFDI.

For Northern Australia, the *CSIRO Fire Spread Meter for Northern Australia* has been developed (Cheney and Sullivan, 2008) and can be used for open grasslands and semi-arid woodlands, largely associated with the tropical and sub-tropical rangelands of northern Australia. Luke and McArthur (1978) noted that these grasslands are coarse thick-stemmed perennial grasses where different curing correction needs to be applied rather than the fine textured annual grasses of the temperate areas further south which can use the 1997 *CSIRO Grassland Fire Spread Meter*. These latter two meters do not provide a numerical index, but rather is limited to determining forward rates of spread.

Studies have consistently recognised the important relationship between rates of spread with wind speed, humidity (and dead fuel moisture content) and temperature both in the laboratory (Beer, 1993) and the field (Cheney and Sullivan, 2008).

Using the Grassland Fire Danger Meter (developed by McArthur), Nobel et al (1980) derived the rate of spread equation as a function of GFDI which can be expressed as :

$$R = 0.13GFDI \tag{2.19}$$

For grassland the flame length is a function of fire-line intensity and is given as:

$$Zl = 1.192\left(\frac{I}{1000}\right)^{0.5} \tag{2.20}$$

The GFDI is also connected to the broader fire danger ratings for forests, with GFDIs exceeding 100 also being described as being at the CATASTROPHIC ratings level.

Studies of historical and modelled grasslands for the ACT were developed for use in computer simulations (GRAZPLAN) which could have application in climate change studies and showed that there were important differences in the predictive GFDI for native perennial grass model, the exotic perennial grass model and the annual grass model (Gill et al, 2010). This derived historical dataset (based on biomass inputs) provided a 54 year period of GFDI and grass fire intensity with wind for the ACT which allowed for regional GFDI considerations. In addition, there is a historical National dataset of GFDIs produced for some weather stations which can be used for regional predictive purposes (Lucas, 2010).

In addition to deterministic approaches, Monte-Carlo ensemble methods have been applied to improve the general statistical fit of grassland fire spread, however, this approach did not give any additional changes to the models but rather gave an understanding of the levels of uncertainty of the grassland models examined (Cruz, 2010).

A notable aspect of the McArthur Grassland and CSIRO Grassland Fire Danger Meters is the inclusion of grassland curing (Purton, 1982). Grassland curing is the proportion of dead material in the sward (which is a visible assessment) and can have a significant effect on fire behaviour. Fires will not generally spread when grasses are less than 50% cured (Cheney and Sullivan, 2008). Curing within the range of 75-95% will provide the greatest effect on fire spread and at 100% curing, the grasses will generally be unable to stand upright, causing the fuel to be structurally less aerated. Clearly, overnight dew and rainfall can have an impact on fuel moisture which will need to ‘dry off’ before fires can spread although in windy conditions, fires may burn at fuel moisture contents of 24%. (Cheney and Sullivan 2008).

Cruz et al (2015) have identified a revised curing coefficient from that of Cheney et al (1998) which is applicable to the CSIRO Grassland Fire Spread Model. As grasslands fall outside the scope of the current study, as they do not apply to forest vegetation. This and other grassland models have not been further considered.

Importantly however, is the CSIRO Fire Spread Meter for Northern Australia which is particularly important for the tropical grasslands and open woodlands of the savannah (rangelands), and may be relevant to the far western parts of NSW (Cruz et al, 2015). Again, this model will not be considered further in the current study; however, it may form part of future research into the semi-arid woodlands in NSW.

2.6 Slope and Fuel Moisture Adjustments

The previous discussion has shown that flame height (and flame length) is determined by rate of spread, which is also adjusted for slope and fuel moisture for DEFFM model (Gould et al, 2007a).

2.6.1Slope correction for DEFFM and FFDM5 models

Early descriptors for forward rate of spread recognised that wind and slope interactions were both significant contributors (Santoni et al, 1999; Nelson, 2002; Nelson, 2015).

Boboulos and Purvis (2009) also conducted laboratory experiments on *Pinus species* fuel beds, which although showed some variation in rate of spread between species, provided some understanding of wind-slope interactions. The angle of flame is also strongly influenced by slope as well as wind (Welker et al, 1965; Weise and Biging, 1996; and Viegas, 2004). However, work to date does not assist with positive slopes greater than 30 degrees.

An adjusted slope factor [exp $(0.069*\theta)$] for rate of spread through early experiments described by Luke and McArthur (1978) have been confirmed by the recent experimental work of Project Vesta (Gould et al, 2007), although there may be some role in relation to fuel types on rates of spread seen in laboratory fuel bed fires (Boboulos and Purvis, 2009).

Sullivan et al (2014) has extended this work and proposed a new model which effectively limits negative slopes to 10^o.

These relationships are assumed to hold true for all Australian vegetation types including grasslands (Cheney and Sullivan, 2008; Sullivan et al, 2014) as well as in North America (Gould, 1991 and Nelson, 2015).

2.6.2 Forest fuel moisture correction for DEFFM

The rate of spread for forest fires using DEFFM also needs to be adjusted for fuel moisture by using (Gould et al 2007a; Cruz et al, 2015):

$$R_{fm}=18.35FMC^{-1.495}Rv \quad (2.21)$$

where:

FMC= (Fine)Fuel moisture content (%); and

R_{fm} = rate of spread adjustment for fuel moisture (kph)

The above relationship between fine fuel moisture(FMC) and adjusted rate of spread is described by Cheney et al (2012) although the relationship observed has been extended in the current study beyond the ranges observed in the Project Vesta experiments and the DEFFM model.

Viney (1991) and Matthews (2013) provide a good compilation for fine fuel moisture research. Fine fuel moisture is considered in equilibrium under given environmental conditions including soil moisture, humidity and temperature (Viney and Cathpole, 1991). For grasslands, dead fuel moisture content can be estimated from relative humidity and temperature of the air (Cheney and Sullivan, 2008). In either case of forest fuels or grasslands, dead fuel moisture will vary throughout the day with changes in humidity and temperature and will require time to equilibrate to the environmental conditions present (Cheney and Sullivan, 2008, Tolhurst and Cheney, 1999). Estimating fuel response times and calculating equilibrium fuel moisture content (FMC) can be undertaken from field data which is comparable to laboratory experiments (Catchpole et al, 2001). Although, there were significant difficulties with Western Australian mallee and Tasmanian button-grass moorlands, it was found that the previous models of Viney (1991) and Nelson(1984) for fuel moisture response times were good for Eucalypt litter.

For calculating fine fuel moisture content (*FMC*) as a percentage under the 1967 FFDM5 model, the following derived multi-variable regression equation applies (Viney 1991):

$$FMC = 5.658 + 0.04651\ RH + 3.151\times10^{-4} RH^3/T - 0.1854\ T^{0.77} \qquad (2.22)$$

The above equation is strictly valid only in the following data domain:

$5\% \leq RH \leq 70\%$

$10\ °C \leq T < 41\ °C$

$42.5 - 1.25T < RH < 94.5 - 1.35\ T$

McArthur (1967) suggested that a lower limit for (dead) fine fuel moisture could be determined to the level of 2%, although Viney (1991) when considering FFDM5 places the lower range at 3%. Sharples et al (2009) developed a linear index (fuel moisture index) based on temperature and humidity, simplifying more complex models and tested this index against FFDI and GFDI models.

By contrast, DEFFM provides three models based on time of year and time of day (1300-1700hrs), other times of the day and year; and night time (Gould et al, 2007b). The three equations were derived from the DEFFM tables (Gould et al, 2007a) for fuel moisture and described by Cruz et al (2015). Matthews (2010) describes the use of the simplified model and notes that tabled models for 1500 hr (3:00 pm), and used in DEFFM (Cheney et al, 2012) have reasonable accuracy but are limited for other time periods.

The three fuel moisture content models for the DEFFM are expressed in Eqs 2.23, 2.24 and 2.25 below.

(a) Model 1 (M1)

$$FMC = 2.76 + 0.124RH - 0.0187T \qquad (2.23)$$

(b) Model 2 (M2)

$$FMC = 3.60 + 0.169RH - 0.0450T \qquad (2.24)$$

(c) Model 3 (M3)

$$FMC = 3.08 + 0.198RH - 0.0483T \qquad (2.25)$$

Model 1 is used when:

- The month is October, November, December, January, February or March;
- The time is from 1300-1700 local daylight savings time (1200-1600 standard time);
- Cloud cover is less than 4/8 (i.e. 4 out of 8 sectors).

Model 2 is used for all other months and all other times during the daylight hours not covered by Model 1. Model 3 is used for night-time.

In Model 3, data is based on three recorded night time observations and overnight dew will likely under predicted fuel moisture until dew has evaporated. (Cruz et al, 2015). For the current study, which is based on 3:00pm RH and Tmax, only Models 1 and 2 will be used.

For the present study, Model 1 is particularly applicable as data is only used for 1500 hour (AEST) and will generally fall into the relevant bushfire season during the period of October – March (Cruz et al, 2015a). Model 2 is also used for the period outside of the October-March fire season. Observations are related to Western Australia and for the current study some extrapolation to earlier spring dates (September) and later in autumn (April) may be possible where overall fire weather conditions prevail.

Cheney et al (2012) and Sullivan (2004) note *FMC* ranges from a low of 'about' 3% to fibre saturation at 35% (Gould et al, 2007a). Cruz et al (2015a) provides a table of predicted daytime fuel moisture content also to 3% (at 5% RH and 40^0C). Matthews (per.comm.) suggested that an absolute limit of 2% could be used in western NSW environments on very hot days and very low humidity. A value of approximately 2% is also seen as a mathematical limit when using extreme conditions in Eq 2.23, especially where temperatures exceed 40^0C.

2.7 Determining Radiant Heat Levels

Radiant heat is one of the major bushfire attack mechanisms. Determining radiant heat exposures (flux) of people and materials is a crucial step in developing protection measures. The role of radiant heat models has been advanced by a number of authors for safety zones (Butler and Cohen, 1998; Zarate et al, 2008) and defendable space (Leicester, 1987; Douglas and Tan, 2005; Syphard et al, 2014) for improving building safety.

The recent approaches for determining radiant heat incorporates the use of fire engineering principles or the 'view factor' method (Zarate et al, 2008) and is set out in Appendix B of the Australian Standard AS 3959-2009 (Standards Australia, 2009) and follows the approach proposed by Douglas and Tan (2005).

Radiant heat transfer is also influenced by atmospheric attenuation arising from CO_2 and water vapour in air(Fuss and Hamins, 2002). Knight and Sullivan (2004) proposed a semi-transparent flame model with a volumetric source of constant flame temperature which uses the same approach as Douglas and Tan (2005) but at smaller scale and compares results with a propane fuelled gas burning experiment. Concern is expressed by the authors that radiant heat may be over-estimated for a flame which is upright and may under-estimate for a tilted flame typical of bushfires. There is insufficient data to determine flame angle arising from wind in forest fires. When contrasting the semi-transparent model proposed by Knight and Sullivan (2004) to that of the ‘opaque model’ (Sullivan et al, 2003), it should be recognised that there can be advantages and disadvantages of both approaches, much of which are inherently similar to both models in many respects.

These issues are recognised largely by the work of Douglas and Tan (2005) which generates an optimum ‘view factor’ for all flame angles. Flame widths are also standardised to 100 metres for bushfire conditions, beyond which there is minimal variation in radiant heat. Flame widths can be reduced where this is justified by local circumstances. This approach is also justified for land-use planning and construction practice, where a conservative approach is warranted.

However, Wotton et al (2012) found that flame temperature varied with height of the flame, rate of spread, fire line intensity and surface fuel. Maximum temperatures were found to be ~1100^{o}C (or ~1475K) at the base with flame temperatures dropping with height within the flame to ~300^{o}C (~675K) at the tip. Some researchers (Knight and Sullivan, 2004) have advocated 1200K as a suitable flame temperature but AS 3959-2009 uses a flame temperature of 1090K. For the present study, flame temperatures are also assumed to be universally distributed across the flame front surface and a flame temperature of 1090K is used in the current study for consistency with AS 3959-2009.

The dimensions of the flame and flame temperature give rise to the application of the Stefan-Boltzmann equation:

$$R_d = t\varphi\varepsilon\sigma T_k^4, \qquad (2.26)$$

where

R_d = radiant heat flux of receiver (kW/m^2),

ε = flame emissivity,

t = transmissivity of air between emitter (flame) and receiver,

φ = view factor,

σ= Stephan-Boltzman constant (5.67 x 10^{-11} kWm^{-2}K^{-4}), and

T_k= flame temperature (in degrees Kelvin)

Although other approaches to radiant heat modelling have been developed (Leicester, 1987), they are not described herein as the method adopted by AS3959-2009 is considered more appropriate as a standardised engineering approach. A comprehensive review of these and other approaches can be found in Ellis (2000).

2.8 Summary

Construction practice for bushfire prone areas requires the application of the Australian Standard AS 3959-2009 which incorporates a site assessment process which currently uses FFDI for forest fire behaviour. This site assessment method also requires consideration of vegetation and fuel loads and local topographical features as input. The continued use of the FFDM5 may under-estimate the potential for bushfire attack under high intensity fires associated with *extreme* events. Although rates of spread using DEFFM can be up to three times that of the FFDM5 we currently do not have an appropriate comparison for flame height. It is therefore important to ascertain what, if any implications arise from the use of both methods for the same conditions related to fuel and weather conditions. Both models adjust rates of spread in the same manner in relation to slope.

In this chapter, bushfire behaviour models for forest fires (which use either the FFDM5, FFBT, DEFFM), grassland fires and shrubland fires have been reviewed.

So as to compare FFDM5 and DEFFM approaches, it will be necessary to develop comparable input parameters for comparing both sets of equations. Due to its similar limitations to FFDM5 and its non-applicability for NSW, the FFBT model will not be assessed in the current study. Table 2.3 below provides an outline of comparable modelling considerations for both FFDM5 and DEFFM.

Table 2.3: Input parameters for determining radiant heat flux and BALs in Australia subject to bushfire attack from forest fires

Model Input parameter		Model	
		FFDM5	DEFFM
Fire weather data	Temperature	√	√
	Wind speed	√	√
	Humidity	√	√
	Fire Danger Indices	√	X
Fuel characteristics	Fuel load	√	X
	Fuel Hazard (hazard score/rating)	X	√
	Fuel height	X	√
	Fuel Moisture	X	√
Topography	Slope adjustment	√	√

The determination of bushfire attack used for planning and construction practice is largely based on determining radiant heat flux which is largely influenced by fuel and fire weather conditions.

In chapter 3 the role of vegetation in both of the forest fire behaviour models (FFDM5 and DEFFM), there classification and general extent across NSW will be reviewed. This chapter also develops a comparative assessment of fuel characteristics for use in both FFDM5 and DEFFM approaches.

Chapter 4 provides a review of the role fire weather has (as inputs for FFDM5 and DEFFM) and also considers the potential implications of climate change on bushfire events.

CHAPTER 3 - VEGETATION CLASSIFICATION AND FUEL ARRANGEMENTS IN NSW

3.1 Introduction

In Chapter 2 a review of bushfire behaviour models for various vegetation classes was considered. These models identified that for forest fires, the two major models to be considered by the current study are the FFDM5 (based on FFDI) and that of DEFFM.

In this chapter a review of vegetation in NSW as a source of fuel is considered as it relates to each of the bushfire models considered in Chapter 2. It has already been established that fuel is measured in terms of fuel loads (tonnes per hectare) for the FFDM5 (Noble et al, 1980) and other non-forest fire behaviour models. DEFFM describes fuel in terms of hazard scores or ratings and near-surface and elevated fuel heights; as well as fuel moisture when considering rates of spread and flame height (Cheney et al, 2012).

Our understanding of Australian (and NSW in particular) vegetation characteristics as a source of fuel is fundamental to our understanding of bushfire behaviour (Luke and McArthur, 1978).

In general, bushfire behaviour can be modelled for:

- Forest fires;
- Scrub/Shrubland fires (including mallee); and
- Grassland fires.

However, these fire behaviour models only apply within the context of the field observations and experiments on available vegetation types. For example, we may apply a forest fire behaviour model to rainforest vegetation, whereas little data exists to justify the application of dry sclerophyll forest fire behaviour observations on such a community (Watson, 2011).

3.2 Australian Vegetation Classification

Vegetation classification systems provide for the ordered grouping of plants and allows for the differentiation of ecological characteristics of plant communities. The criteria used for classification of plant communities may include a combination of structure, physiognomic and floristic features (Keith 2004). The structural aspects of vegetation classification arise from the mixture of growth forms or varying heights and the spacing between plants (Walker and Hopkins, 1990). Like all classification systems, they operate at a hierarchical level with increasing levels of differentiation when describing the macro against the micro scale and with different emphasis based on the observers bias. Vegetation classification systems in Australia go back to the 1940s (Beadle 1948; Keith 2002) and 1950s (Costin, 1954; Walker and Hopkins, 1990) but the most enduring classification system has been that advanced by Specht (1974) and AUSLIG (1990), which together form the basis of the National Vegetation Inventory (NVI) System (Department of the Environment and Water Resources, 2007). Under the NVI system there are 23 major vegetation groups identified nationally. A modified version of this national approach based on the AUSLIG classification is commonly used for the assessment of vegetation based on structural considerations and has been used within AS3959 (2009).

Attempts have also been made in North America and Australia to develop classification for surface fuels (Lutes et al, 2009), fine fuel mosaics (King et al, 2008;) and landscape ecosystems (Stottlemeyer et al, 2009), however, the aim of these classification systems are largely limited to assisting in prescribed burning for property protection with some used in the determination of bushfire behaviour for uncontrolled natural wildfires(see Scott and Burgen, 2005).

More recently, Gould and Cruz (2012) attempted to develop an Australian Fuel Classification system based on NVI vegetation classes and the spatial arrangements of fuel. Their approach is largely based on the Specht (1974) vegetation classes but includes urban fuels and other non-native vegetation.

Where forest vegetation formations are identified, fuel mass, fuel arrangement and overall structure (including height), fuel thickness, the proportion of living and dead fuel in the fuel bed, fuel moisture and species composition can all influence fire behaviour (Watson, 2012, Gould et al, 2007a).

When FFDM5 is used, the major input is in relation to fuel load which have been separated into understorey fuels (surface, near surface and elevated fuels with bark) and canopy fuels as a separate component (AS3959, 2009). DEFFM requires input of fuel moisture, hazard score (or rating) and elevated fuel components.

Forest (and other) fires readily consume the fine fuel components allowing fires to ignite and spread rapidly where the fuel moisture content allows. Moisture content of the surface fuel layer (approx. 1 cm depth) should generally be less than 22% for fire initiation (Sullivan et al, 2012), however, the role of slope and wind are also significant contributors (Viegas, 2004), especially for grassland (Cheney and Sullivan, 2008). Fuel moisture for forests have generally been limited to dead fuel moisture content of greater than 2% (McArthur, 1967; Cheney et al, 2012). Heavier fuels respond to seasonal rainfall and drying (Sullivan et al, 2012) and can contribute to residual radiant heat after the passage of a fire (Sullivan et al, 2002).

When considering heath and mallee vegetation, the relationship of fuel moisture with fire behaviour is less clear and the initiation of fire may be related to a threshold fuel moisture value, rather than a progressive relationship between fuel moisture, wind and rate of spread as seen in forests and grasslands (Plucinski et al, 2010). These issues are considered in more detail in Chapter 2, however, for fuel measurement purposes, heath, scrubs and shrublands are all differentiated by height of vegetation, which is correlated with fuel load, age, bulk density, cover and percentage of dead fuel (Catchpole, 1998).

The map of Australian vegetation used with the NVI System is shown at Figure 3.1(Department of Environment and Water Resources, 2007).

The NVI system has its limitations in that vegetation within these classes is not uniform across the range of vegetation types within the identified landscape or region.

Vegetation structure and fuel characteristics may vary with local changes in soil, aspect or disturbances; and some vegetation types may exhibit extensive variability across Australia making classification difficult (Gill, 2012). These difficulties have led to new classification systems. For non-rainforest vegetation, tallest stratum, emergent, mid and lower stratum, growth form, height and cover (e.g. crown cover) or separation can be used to better describe sclerophyllous vegetation (Walker and Hopkins, 1990). Gill (2012) has also identified three distinct, discontinuous regions for the grouping of ‘southern forests’, of which NSW forests are one.

These NSW southern forests are found from the Queensland border to Victoria (and the ACT), within the coastal and sub-coastal areas of the State.

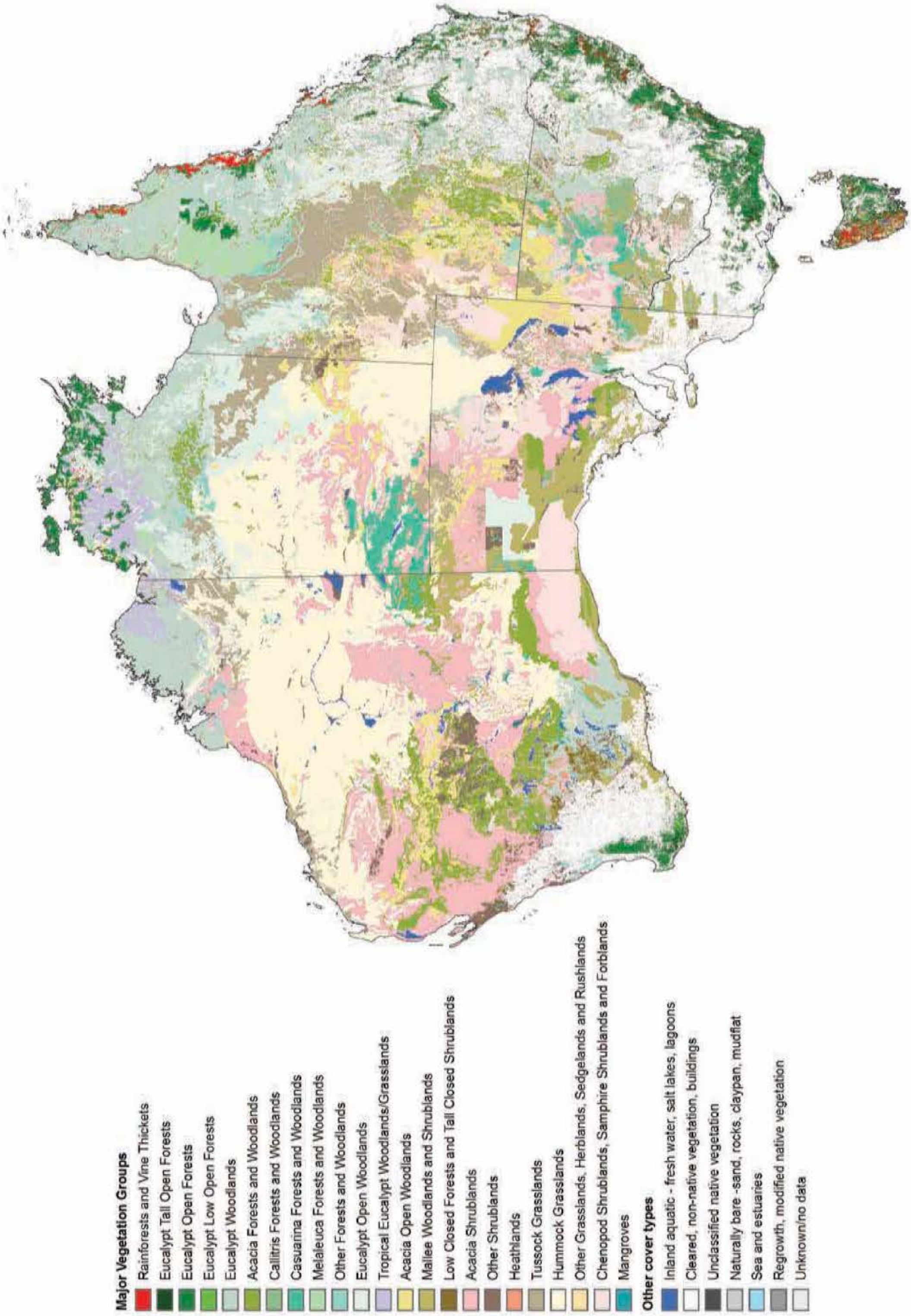


Figure 3.1Map of vegetation classes under the National Classification System (Dept. of Environment & Water Resources, 2007)

3.3 Biogeographic Model of Australian Fire Regimes.

Fire is a natural phenomenon in the Australian landscape, however, the frequency, seasonality, extent and intensity of bushfires varies within that landscape (Gill, 2012). This pattern of fire regimes can demonstrate broad biogeographic variability, due to influences of four key 'switching' mechanisms (Bradstock, 2010). These switching mechanisms are:

- Biomass growth with surface and near-surface fuels critical in the spread of fire;
- Availability to burn due to conditions such as drought (affecting fuel moisture) which increases vertical and horizontal connectivity and may be driven by multi-decadal climatic influences such as El Nino Southern Oscillation (ENSO) or the Indian Ocean Dipole (IOD) in temperate forests;
- Fire weather arising from severe ambient weather conditions, making ignition more likely with latitude and rainfall (i.e. decreasing latitude and decreasing rainfall increasing fire weather in SE Australia); and
- Ignition arising from both lightning and anthropogenic sources, with higher anthropogenic ignition sources associated with population density and land-use, with lower rates in more rural areas.

These patterns of switching vary with biogeographic features, with larger low intensity fires occurring across the northern parts of Australia, and fewer, but higher intensity fires in the more temperate forests of the south-east and south-west. Fuel accumulation is rapid in these temperate forests after fire and reach sufficient litter to fuel intense fires within 5-10 years (Price and Bradstock, 2012) with severe fires being governed more by drought and ambient weather at the time of ignition (Bradstock, 2010).

The linkages between these four switching mechanisms at the macro-scale, can assist in providing a foundation to sustainable fire management to protection human life, property and environmental values (including biodiversity and carbon stocks).

An Australian fire regimes map has been derived by Murphy et al (2012) from the NVI map illustrated in Figure 3.1. This revised map can be found at Figure 3.2 and reflects the impacts of the four switch model described by Bradstock (2010) within the Australian landscape.

Most fire regimes are characterised by frequent low intensity surface fires often associated with the grasslands (and savannah) of northern Australia, with less frequent but more intense fires (>20,000kWm^{-1}) in the south-east (including eastern NSW). Fire regimes are rare within the mulga woodlands, mallee scrub and chenopod shrublands of the semi-arid and arid interior (Murphy et al, 2012)

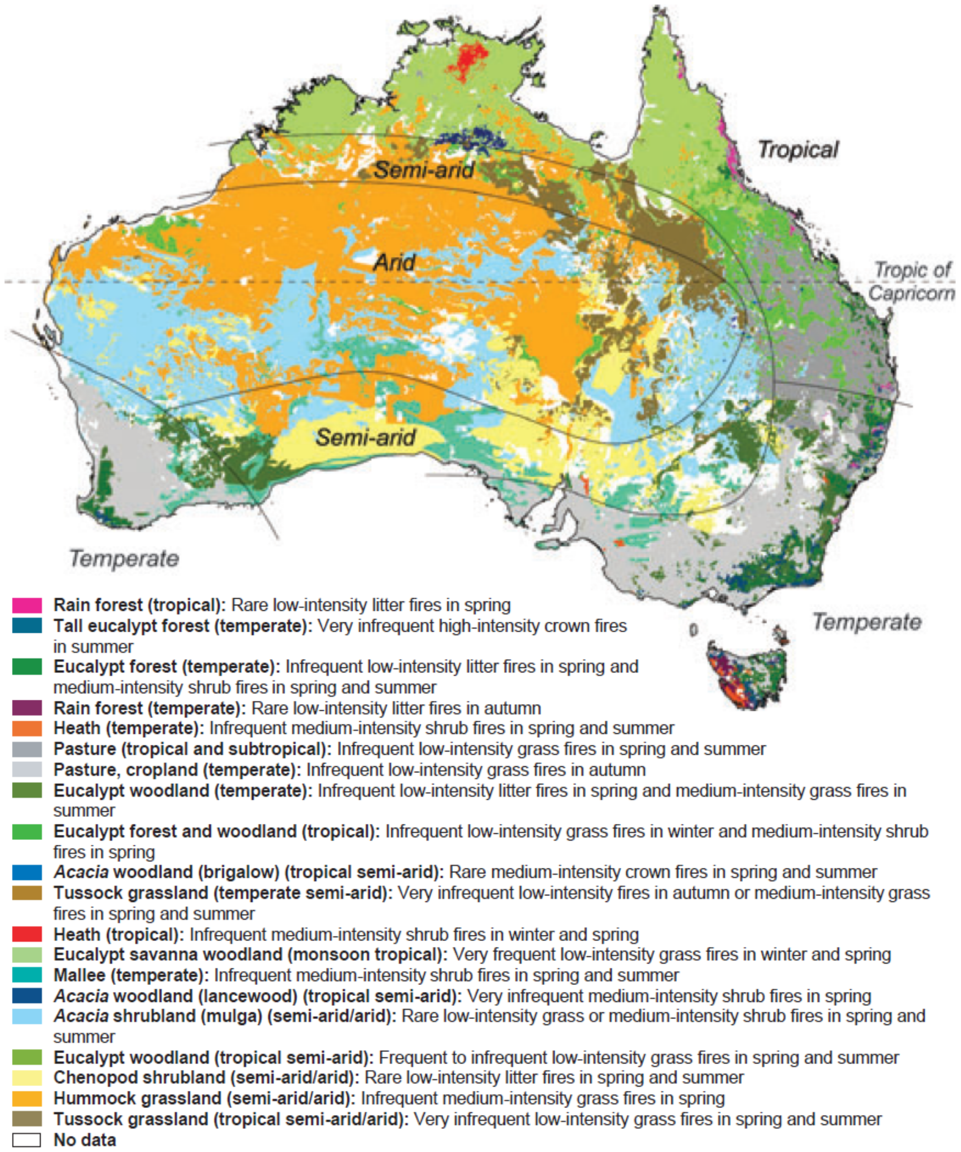


Figure 3.2 Distribution of major fire regime niches of Australia (Murphy et al, 2012)

It can be seen in Figure 3.2 that for NSW, the western extent of the State has the arid and semi-arid vegetation groups described above, the central parts of the State are dominated by pasture and grassy woodlands, and the east by temperate eucalypt forests.

3.4NSW Vegetation Formations

Early attempts at describing vegetation classes in NSW were based on isolated areas of interest (Keith, 2004) or broad geographic landscapes (Anderson, 1968). For bushfire assessment purposes, a common structural descriptive basis of vegetation is preferable; however, vegetation within the landscape is often differentiated on the basis of species composition and mix as well as structure (Walker and Hopkins, 1990). Of relevance for the current study is any system which can best differentiate the New South Wales vegetation classes, especially for forest vegetation. The system used in this study is that provided by Keith (2004) and describes vegetation formations (or sub-formations) and there classes. A map of the extent of NSW vegetation formations using the system of Keith (2004) is shown in Figure 3.2.

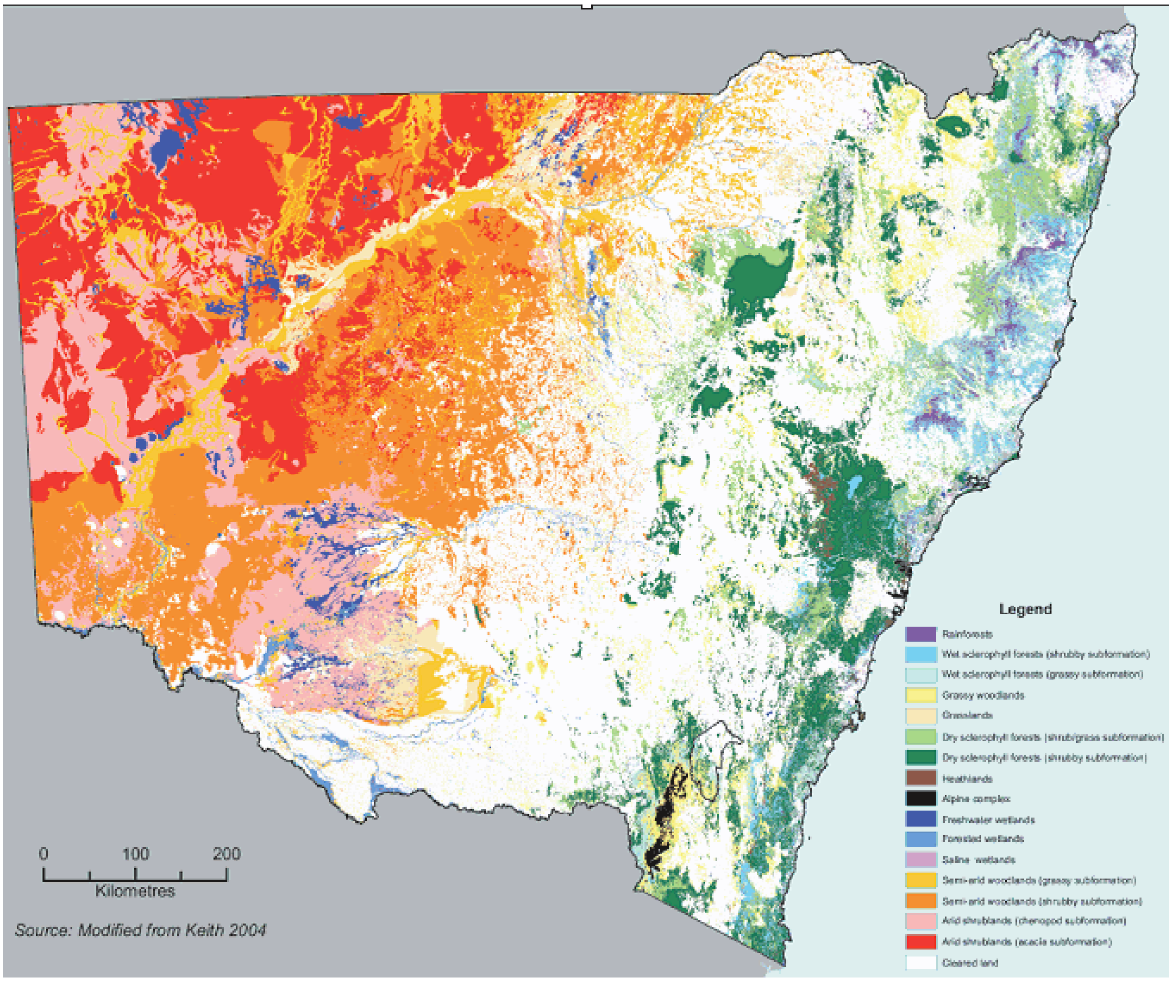


Figure 3.2: Extent of Vegetation Formations in NSW (Keith, 2004)

There are 17 vegetation formations and sub-formations identified by Keith (2004) identified in the current study, however, not all of these formations constitute forest vegetation. A description of the various vegetation classes identified by Keith (2004) and of interest to the current study are discussed in detail in section 3.5 below. The mapping in Figure 3.2 demonstrates that the various WSF and DSF forest formations are absent in the western part of the State as described by Gill (2012), with woodlands appearing more widespread.

Fuel assessment characteristics have been developed from a literature review by the University of Wollongong (Watson, 2009, Watson 2011, Watson, 2013 and others) on behalf of the NSW Rural Fire Service. The compilation of these various sources into a single set of fuel characteristics has been undertaken at section 3.5 as part of the current study.

3.5Assessing Fuel Load and Fuel Structure

In Chapter 2, we demonstrated how bushfire behaviour depends on fuel load and/or fuel structure.

For the purposes of this study, forest (including grassy woodland) fuels loads (tonnes per hectare) for the FFDM5, will be described in terms of:

- Sub-canopy fuels (including bark, surface (litter), near surface and elevated fuels);
- Canopy fuels comprising tree cover (dominant and sub-dominant or intermediate); and
- Total fuels, which includes sub-canopy and canopy fuels.

For the DEFFM fuel components, this study will describe fuels in terms of hazard scores and elevated fuel heights for flame height purposes. For forests, Gould et al (2011) has four fuel layers identified for DEFFM being:

- over-storey and intermediate canopy bark fuel,
- elevated fuel layer,
- near-surface fuel layer, and
- surface fuel layer.

The structural components of the DEFFM can be seen in Figure 3.3 which is taken from Gould et al (2011). The FFDM5 components are also shown with sub-canopy below the over-storey fuels.

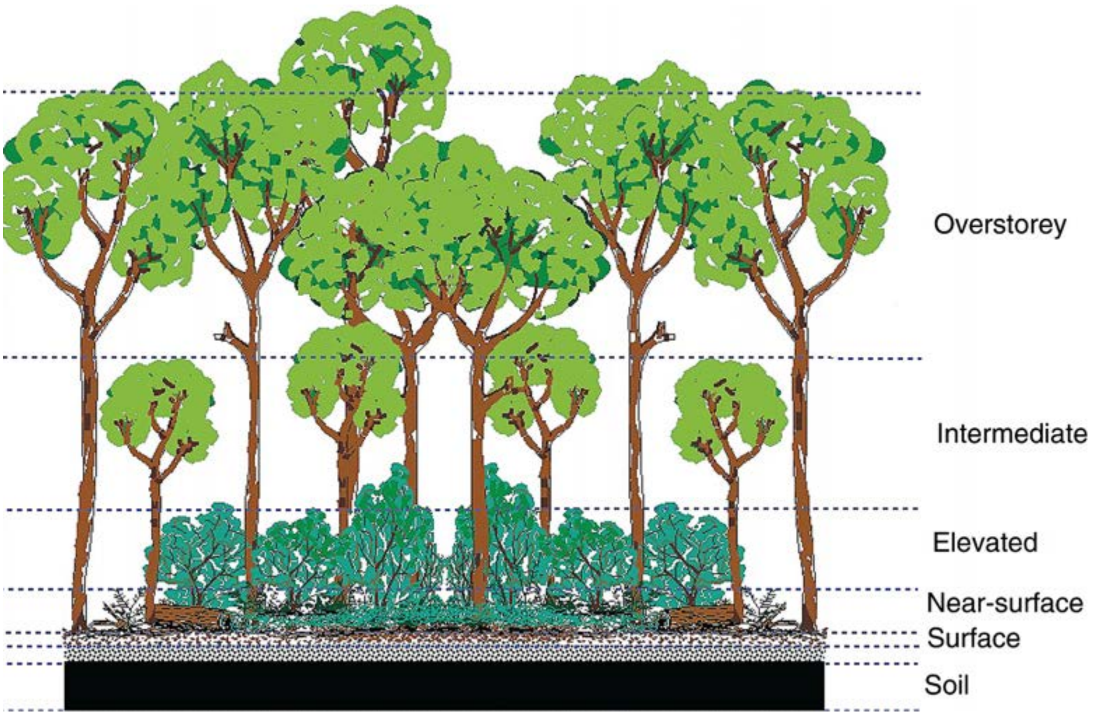


Figure 3.3: Structural fuel components of forest vegetation classes (DSF) (source: Gould et al, 2011)

3.5.1 Sub-canopy fuel load assessment

Recent work by the University of Wollongong (Watson, et al, 2012) has assisted in providing data on fuel characteristics for a range of vegetation formations including forests, woodlands, rainforests, scrubs (and shrublands), wetlands and semi-arid woodlands. For fuel load accumulation in forests and woodlands, fuels will generally follow an exponential saturation model and that the curve expressing fuel loads will be asymptotic over time (Watson, 2005; Watson, 2011). The point of equilibrium occurs when fuel deposition equals fuel decomposition, although there will be some variation over time (season) and space (Tolhurst and Cheney, 1999) with a wide variability within the range of observations (Good, 1994). During periods of drought for example, increased leaf drop and reduced decomposition may occur, and on steeper slopes, gravity, wind and water may transport fuels to lower points in the landscape such as in creek lines. Areas may also have rocky outcrops which complicate depositional rates.

The expression for fuel accumulation below canopy follows the Olsen model described by Watson (2011) and others (Good, 1994):

$$W_t = Limit(1 - e^{-kt}) \quad 3.1$$

where W_t is the fuel load (in tonnes per hectare, or t/ha) at time t for the period since last fire in years, *Limit* is the steady state fuel limit (also in tonnes per hectare) and k is the fuel accumulation rate towards the steady state fuel limit. Parameter k is related to the annual load deposition rate L (tonnes/Ha/year) by the following:

$$k = \frac{L}{Limit} \quad 3.2$$

Alternatively, k can be measured by sampling post fire fuel loads and fitting the sample points to the model. Decomposition rates can be measured directly through experimental studies by placing mesh bags in-situ on the floor of the forest (or other vegetation) for a known period, noting the progressive loss of fuel over time (Watson, 2011).

The Olsen model as expressed in Eq. (3.1) assumes complete fuel removal as a result of the last bushfire event. However, in most cases some residual fuel may exist in the canopy or elsewhere. To account for the residual fuel, a modification of the Olsen equation has been described by Watson (2011). The subsequent equation is given as:

$$W_t = Initial + (Limit - Initial)(1 - e^{-kt}) \quad 3.3$$

The range of fuel loads observed within a specified vegetation community can vary widely (Watson, 2005 and Good, 1994) and hence fuel loads are best described in terms of average fuel loads for the period of steady state conditions when used for land-use planning purposes.

Most work has been concerned with average fuels below the canopy, which are well expressed by the Olsen equation (Watson, 2011). However, where land use planning is concerned the measurement of fuel should also be about total fuel availability, incorporating both overall fuel loads (Hines et al, 2010) and canopy fuels (RFS, 2006). The term overall fuel has been used to distinguish all sub-canopy fuels (litter fuels, elevated fuels, bark fuels and surface fuels) for the purposes of fuel treatment through prescribed burning (Hines et al, 2010). Because the fuel guides (e.g. Hines et al, 2010) are traditionally used for prescribed burning, the term overall fuel hazard has often been used for land management purposes.

3.5.2 Assessing canopy fuels

Canopy fuels are critical in the assessment of fire behaviour at VERY HIGH fire danger ratings (FFDI>25) (Luke and McArthur, 1967) and can form part of the fine fuel component of the continuous flaming zone (Pastor et al, 2003). The two identified methods of determining fuel load for forest canopy which can be used for the FFDM5 are the annual litter fall and leaf lifespan method, and the biomass study estimation method (University of Wollongong, 2013).

The ‘annual litter fall and leaf lifespan’ method assumes a steady state of leaf replacement within the canopy. Most of the fine fuel on the forest floor is made up of leaf litter with twigs and seeds forming smaller amounts (University of Wollongong, 2013). Under this method, canopy fuel load is estimated by the product of the annual litter fall and the average lifespan.

Biomass study estimation method seeks to isolate the leaf component of the overall above ground biomass (AGB) but may underestimate the canopy fuel component, which comprises twigs and leaves (University of Wollongong, 2013).

It may also be possible to determine canopy fuel from the leaf area index described by the University of Wollongong study. However, exploration of this possibility was not accomplished due to insufficient data (University of Wollongong, 2013).

For the purposes of land use planning and bushfire protection, it is assumed that 100% of the canopy fuel and 100% of the bark fuel will be consumed.

3.5.3 Fuel hazard score and hazard ratings

DEFFM uses a combination of numerical hazard scores and categorical hazard ratings (see Section 2.2.2 of this thesis and Cheney et al, 2012). These hazard scores (or ratings) should be assessed over the period of accumulation when used for land-use planning and construction practice. Hazard score systems may also follow the general Olsen equation, i.e. Eq.(3.1) above. Hazard scores range from 0 to 4, whereas hazard rating were originally expressed as ranging from LOW-EXTREME (Gould et al, 2007b) and can be categorized as ranging from 1-5.

Table 3.1 provides a comparison of fuel hazard scores and ratings under the DEFFM.

Table 3.1: DEFFM hazard ratings and score ranges used in fuel assessments (Cruz et al, 2015a)

Fuel Hazard Rating Number and Category	Fuel Hazard Score Range (used in Eq 2.9 above)
1. LOW	≤1.5
2. MODERATE	>1.5 and ≤2.5
3. HIGH	>2.5 and ≤3.5
4. VERY HIGH	>3.5 and ≤ 3.75
5. EXTREME	>3.75 and 4

The hazard scores and ratings in DEFFM are also related to available fuel loads (t/ha) within these layers. Hines et al (2010) and the South Australian Department of Environment and Natural Resources (2012) have further developed the use of fuel assessment guidance which incorporates DEFFM scoring within a visual assessment approach which is more comprehensive than that of Gould et al (2007b) and conforms to the variation described by Cheney et al (2012). The revised overall fuel hazard rating (and score) for sub-canopy fuels developed by Hines et al (2010) also range from LOW to EXTREME. The rating depends not only on fuel load but also on fuel structure. Table 3.2 presents the conversion table from fuel hazard rating into fuel load (t/Ha) for the 4 structural layers.

Table 3.2: Conversion of fuel hazard ratings into fuel load (t/ha) and structural layers (source: Hines et al, 2010).

	Fuel hazard rating				
Fuel	**Low**	**Moderate**	**High**	**Very High**	**Extreme**
Bark	0	1	2	5	7
Elevated	0–1	1–2	2–3	3–5	5–8
Near-surface	1–2	2–3	3–4	4–6	6–8
Surface	2–4	4–10	8–14	12–20	16–20+

These fuel loads can be used directly into Eqs. (2.4) and (2.5) for the FFDM5 model. However, for DEFFM, the above hazard ratings also can be used to provide overall hazard scores as shown in Table 3.1 above.

For NSW, Watson (2011) has broken down each fuel hazard layer and as such, future fuel load and hazard rating assessments will need to incorporate such fuel characteristics based on Table 3.2.

3.6 Keith Vegetation Classes

Different vegetation classes, even within their formations, will potentially exhibit differing fuel characteristics, both in terms of structure (layers) and fuel loads. The NSW system of vegetation classification has been subject to two main approaches being that of the *NSW Vegetation Classification and Assessment* (NSWVCA) by the Royal Botanic Gardens (Benson, 2006; Benson, 2010) and the *Compilation Map of Native Vegetation of NSW* by the National Parks and Wildlife Service (Keith, 2002). The complexity of vegetation has been a key issue in any classification system (Tozer et al, 2010). It was reported that in the NSW Western Plains alone, there were 213 plant communities (Benson, 2006).

For NSW, the challenge has been to link the appropriate fuel classification under the system adopted by AS 3959-2009, with that of local vegetation classification (RFS, 2009a). For the current study, vegetation will be classified under the system developed by Keith (2004) which is also adopted by others in the development of fuel load and fuel arrangement characteristics (Watson, 2011; Watson, 2011a; Watson et al, 2012; Horsey and Watson, 2012; and Watson, 2013). Under this system, vegetation is classified into 17 formations (and sub-formations), 99 vegetation classes (Keith 2004) and down to approximately 1500 plant communities (Benson, 2006). Data is often limited on individual communities; however, vegetation classes within formations can provide an improved guide for land use planning purposes and has been adopted in the current study.

Fuel data was compiled in the current study from 6 reports produced under contract to the NSW Rural Fire Service by the University of Wollongong(Watson, 2011; Watson, 2011a; Watson et al, 2012; Horsey and Watson, 2012; Watson, 2013; and University of Wollongong, 2013).

Tables 3.4 – 3.7 provides a compilation assessment of these fuel characteristics for each forest or grassy woodland vegetation class within the relevant formations (or sub-formations) described by Keith (2004). Fuel assessments were compiled using the inputs of these reports in terms of fuel loads (for FFDM5) and fuel hazard scores (for DEFFM).

Fuel loads (average) are expressed in terms of tonnes per hectare. Fuel structure is described in terms of fuel hazard score for relevant structural elements (surface, bark and near-surface fuels). This will allow direct comparison between the FFDM5and DEFFM models for key bushfire behaviour characteristics of rates of spread and flame height.

For each vegetation class considered, there is an assessment of average fuel load and fuel structure over a 25-30 year period as well as the distribution of these classes within each fire weather area. The 25-30 year time span is used as a reasonable planning period, although in some vegetation classes (e.g. rainforests) longer periods may be warranted. The aim is to obtain fuel related data expressed as its steady state fuel accumulation period.

The important forest and grassy woodland formations and classes are discussed below. These are described in terms of ecological characteristics, regional distributions and fuel characteristics.

3.6.1 Wet sclerophyll forest (WSF) formations and classes

a) Ecological characteristics

Keith (2014) identifies 9 WSF vegetation classes (within two sub-formations) found over a wide area of northern and southern coastal NSW and the escarpment areas of the Australian Alps. Structurally WSFs have high open canopies dominated by tall (>30 metre) eucalypts with straight trunks and an extensive understorey of soft leaved shrubs, herbs and ferns (RFS, 2006). There is often a sub-dominant canopy of rainforest species and WSFs can usually be found on moderately fertile soils with high (>900 mm) annual rainfall. They may be found in more sheltered locations on more easterly aspects however they may also be found on flat areas of low relief on the North Coast of NSW.

b) Regional distribution

AS 3959-2009 includes Tall Open Woodlands within this classification (SAA, 2009) and these may form some of the more grassy sub-formations in coastal and escarpment areas (Keith, 2004). The Shrubby sub-formation classes are typical of alpine and tableland areas (RFS, 2006). The distribution of WSFs in NSW are shown in Figures 3.4 and 3.5.

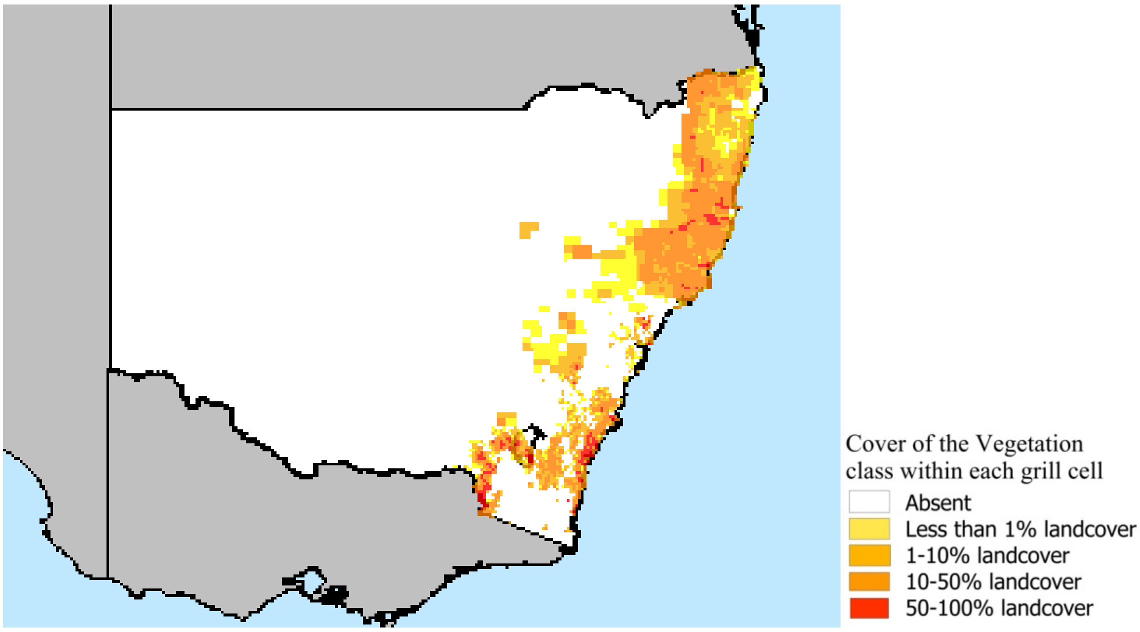


Figure 3.4: Distribution of WSF (grass/shrub) in NSW (source: NPWS, 2008)

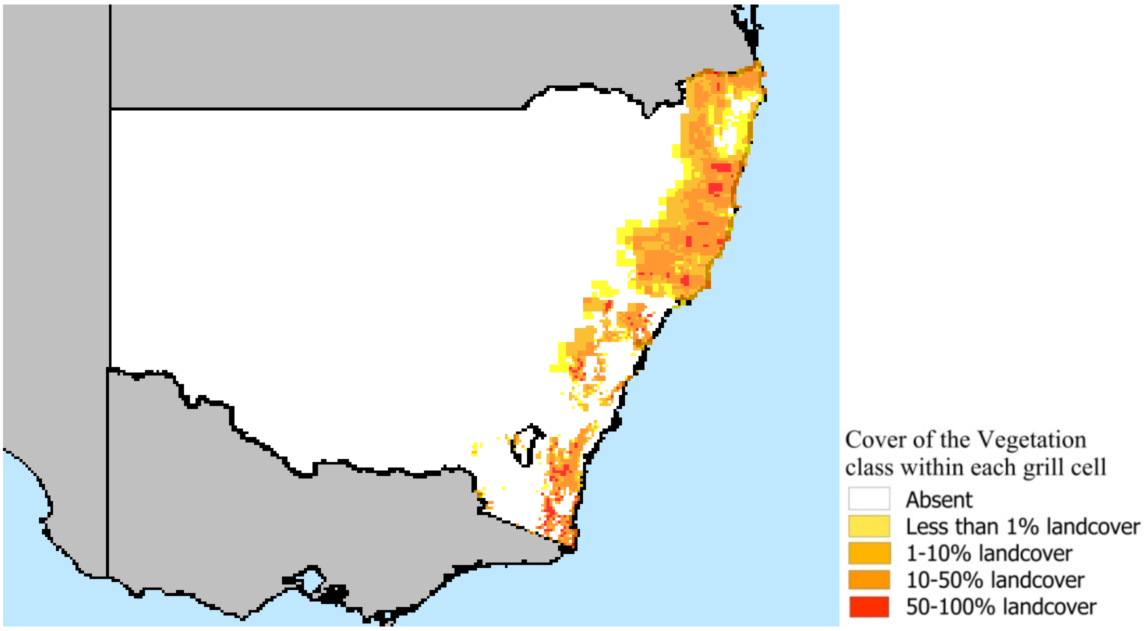


Figure 3.5: Distribution of WSF (shrub) in NSW (source: NPWS, 2008)

c) Fuel characteristics

The fuel loads range from just under 30 tonnes per hectare to over 36 tonnes per hectare across all classes. The overall hazard scores range from 3.5 to 4.0 under the DEFFM system (Gould et al 2007a) and described by Hines et al (2010).

The tabulated results for fuel loads and hazard scores are shown in Table 3.3 below.

Table 3.3: 25 year Fuel loads and hazard scores of NSW WSFs (derived from Watson et al 2012, UoW 2013)

Vegetation Class (Keith,2004)	**25 year average Fuel Load (tonnes/Ha)**					**25 year Fuel Hazard Score**			
	Surface	Elevated	Bark	Canopy	Total	Surface	Elevated	Bark	Total
North Coast WSF	19.00	2.93	3.67	10.10	35.7	3.72	3.15	3.00	4.00
South Coast WSF	19.00	2.93	3.09	10.10	35.1	3.72	3.15	2.00	3.56
Northern Escarpment WSF	19.00	2.93	4.25	10.10	36.3	3.72	3.15	3.00	4.00
Southern Escarpment WSF	19.00	2.93	3.79	10.10	35.8	3.72	3.15	3.00	4.00
Northern Hinterland WSF	18.00	1.96	3.31	9.60	32.9	3.65	3.01	3.00	4.00
Southern Lowland WSF	18.00	1.96	3.03	9.60	32.6	3.65	3.01	3.00	4.00
Northern Tableland WSF	18.00	1.96	3.25	8.10	31.3	3.65	3.01	2.00	3.50
Southern Tableland WSF	18.00	1.96	1.92	8.10	30.0	3.65	3.01	2.00	3.50
Montane WSF	23.85	1.96	2.47	8.00	36.3	3.98	3.01	2.00	3.51

3.6.2 Dry sclerophyll forest (DSF) sub-formations and classes

a) Ecological characteristics

DSFs are open forests often dominated by eucalypts 10 – 30 metres in height with crowns that touch or overlap and a prominent shrub layer of hard-leaved species. They can be found on infertile soils with rainfall generally higher than 500 mm per annum and can be found on the coast, tablelands and the western slopes (RFS, 2006).

DSFs have been divided into two sub-formations: a shrub/grass sub-formation which has conspicuous grasses in the understorey in conjunction with a substantial shrub layer of hard leaved plants, and a shrubby sub-formation with the understorey dominated by hard leaved shrubs and a sparse ground cover, usually associated with sandy infertile soils on exposed (westerly) slopes (Keith, 2004).

There are 24 classes within these two sub-formations, with one on the North-western slopes being described as woodland, because of its sparse canopy (Keith, 2004). One of the classes is also dominated by Acacia (Wattle) and is described as being Southern Wattle DSF which grows as small patches on rocky slopes or gorges, otherwise surrounded by eucalypt forests (Keith, 2004). This class has not been assessed due to its restricted nature and lack of adequate information of fuel characteristics.

Photo 3.1 below is a photo illustrating the grass/shrub DSF sub-formation, whereas Photo 3.2 illustrates the shrubby DSF sub-formation.

b) Regional distribution.

Generally, dry sclerophyll forests are more broadly distributed than wet sclerophyll forests. The DSFs are found on both the east and west of the great divide, with a progressively lower percentage of land cover to the west. Much of the area in the central parts of the State have been extensively cleared for agriculture and pastoral activities.

Photo 3.1: Grass/shrub (Cumberland) DSF with elevated fuel less than 2 metres in height (photo by author)

Photo 3.2: North Coast DSF with elevated fuel greater than 2 metres in height (photo by author)

The distribution of grass/shrub DSF sub-formation vegetation in NSW is shown in Figure 3.6 below. The distribution of shrubby sub-formation of the DSF in NSW is shown in Figure 3.7.

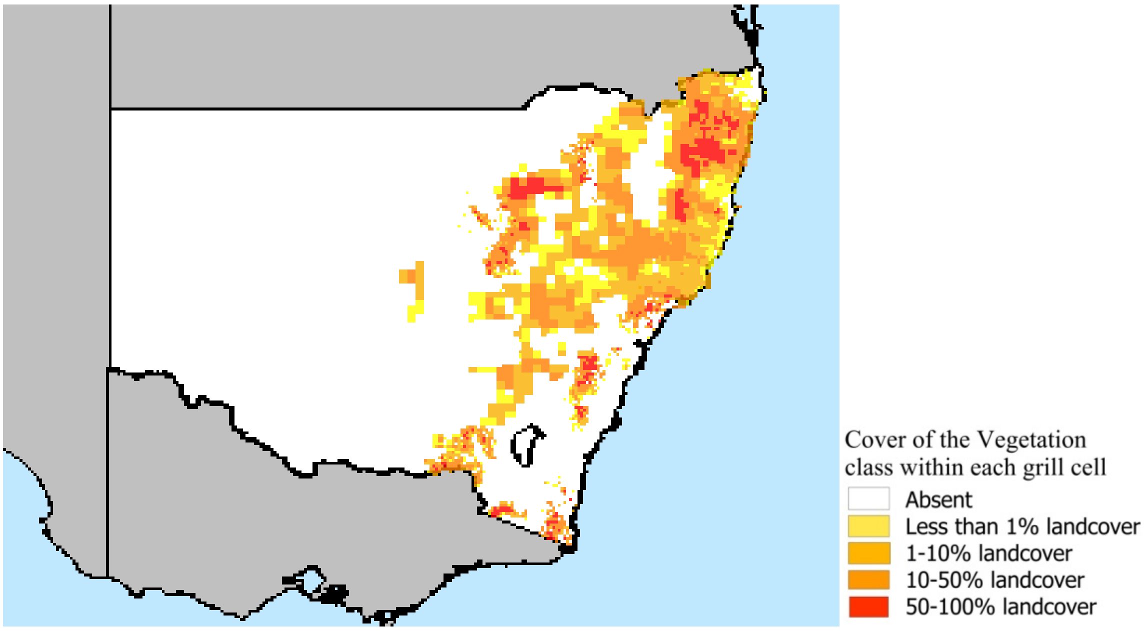


Figure 3.6: Distribution of grass/shrub sub-formation DSF in NSW (source: NPWS, 2008)

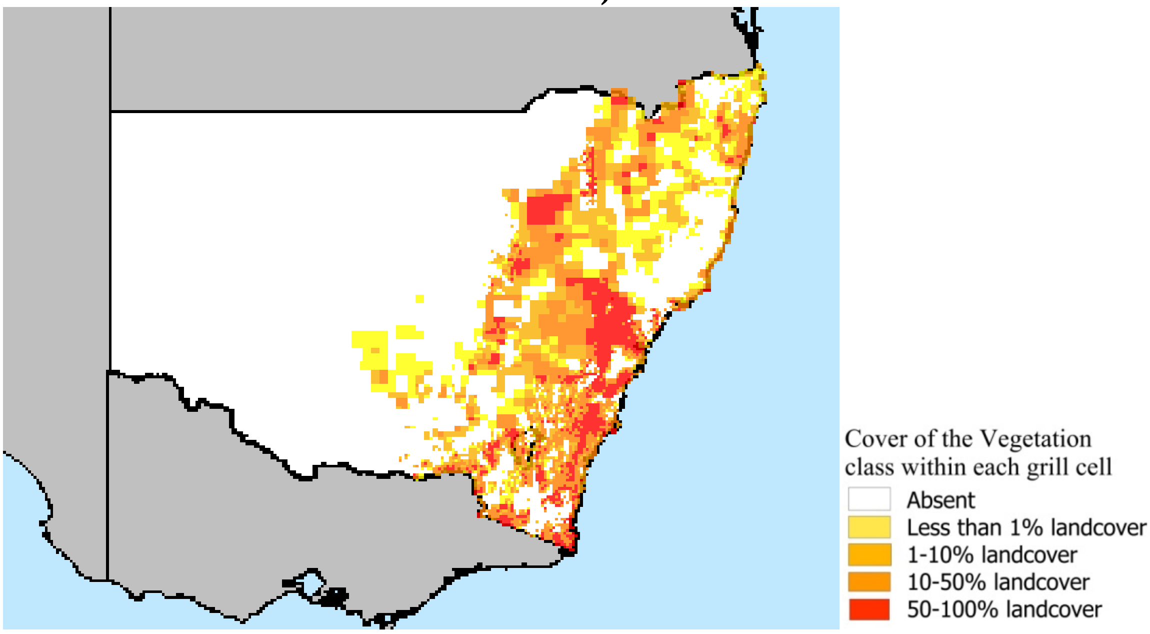


Figure 3.7: Distribution of shrubby sub-formation DSF in NSW (source: NPWS, 2008)

c) Fuel characteristics

The grass/shrub sub-formation of the DSFs have 11 classes and fuel loads generally lie around 25 tonnes per hectare and hazard scores of 3.20. The exceptions can be found in the Pilliga Outwash DSF which has a lower hazard score of 2.03 and a fuel load of 10.96 tonnes per hectare.

The assessment of fuel characteristics for grass/shrub sub-formation DSFs can be seen in Table 3.4 below. In most cases, fuel loads will increase slightly with the steady state period approximating 30 years rather than 25 years used in this study. Elevated fuel heights are considered to be less than 2 metres in height (Watson et al, 2012).

Table 3.4: Fuel loads and hazard scores of NSW DSFs grass/shrub sub-formation (derived from Watson et al 2012, UoW 2013)

Vegetation Class (Keith,2004)	**25 year average Fuel Load (tonnes/Ha)**					**25 year Fuel Hazard Score**			
	Surface	Elevated	Bark	Canopy	Total	Surface	Elevated	Bark	Total
Clarence DSF	11.99	1.99	2.25	8.80	25.0	3.19	3.03	2.00	3.2
Hunter-Macleay DSF	11.99	1.99	1.69	8.80	24.5	3.19	3.03	2.00	3.2
Cumberland DSF	11.99	1.99	2.05	8.80	24.8	3.19	3.03	2.00	3.2
Southern Hinterland DSF	11.99	1.99	2.97	8.80	25.8	3.19	3.03	2.00	3.2
Northern Gorge DSF	11.99	1.99	2.84	8.80	25.6	3.19	3.03	3.00	3.2
Southern Gorge DSF	11.99	1.99	2.84	8.80	25.6	3.19	3.03	2.00	3.2
Central Gorge DSF	11.99	1.99	2.84	8.80	25.6	3.19	3.03	2.00	3.2
New England DSF	11.99	1.99	2.31	8.80	25.1	3.19	3.03	2.00	3.2
North-west Slopes DSW	11.99	1.99	1.59	8.80	24.4	3.19	3.03	1.00	3.2
Pilliga Outwash DSF	5.99	0.99	1.38	2.60	11.0	2.05	2.61	2.00	2.0
Upper Riverina DSF	11.99	1.99	2.17	8.80	25.0	3.19	3.03	2.00	3.2

There are 14 classes in the shrubby DSF sub-formation and generally have higher fuel loads than the grass/shrub sub-formation. The derived fuel characteristics are given in Table 3.5.

Table 3.5: Fuel loads and hazard scores of NSW DSF shrubby sub-formation (derived from Watson et al 2012, UoW 2013).

Vegetation Class (Keith,2004)	**25 year average Fuel Load (tonnes/Ha)**					**25 year Fuel Hazard Score**			
	Surface	Elevated	Bark	Canopy	Total	Surface	Elevated	Bark	Total
Coastal Dune DSF	17.99	2.50	2.09	8.40	31.0	3.65	3.11	2.00	3.5
North- Coast DSF	16.19	4.87	3.45	3.50	28.0	3.52	3.38	3.00	4.0
Sydney Coastal DSF	16.19	4.87	2.37	3.50	27.0	3.52	3.38	2.00	3.5
Sydney Hinterland DSF	16.19	4.87	2.48	3.50	27.0	3.52	3.38	2.00	3.5
Sydney Sand Flats DSF	17.99	2.50	0.57	8.40	29.5	3.65	3.11	1.00	3.5
South Coast Sands DSF	17.99	2.50	1.92	8.40	30.8	3.65	3.11	2.00	3.5
South-east DSF	11.90	4.96	3.22	7.60	27.7	3.17	3.39	3.00	4.0
Southern Wattle DSF	11.90	4.96	3.22	7.60	27.7	3.17	3.39	3.00	4.0
Northern Escarpment DSF	16.19	4.87	3.09	3.50	27.7	3.52	3.38	2.00	3.5
Sydney Montane DSF	16.19	4.87	2.53	3.50	27.1	3.52	3.38	2.00	3.5
Northern Tableland DSF	19.55	2.45	3.02	5.80	30.8	3.73	3.10	3.00	4.0
Southern Tableland DSF	19.55	2.45	2.42	5.80	30.2	3.73	3.10	2.00	3.6
Western Slopes DSF	12.29	2.45	0.80	3.00	18.5	3.20	3.10	0.00	3.3
Yetman DSF	12.29	2.45	0.81	3.00	18.6	3.20	3.10	1.00	3.3

Fuel loads are generally approaching 30 tonnes per hectare. Like the grass/shrub sub-formation, fuel loads do not reach maximum until about 30 years, hence fuel loads will in many cases exceed those identified in Table 3.5 below. Elevated fuel heights generally exceed 2 metres for shrubby sub-formation DSFs (Watson et al, 2012).

Fuel hazard scores for shrubby DSFs are generally higher than the grass/shrub sub sub-formation and lie within the range of 3.5-4.0. The elevated fuels are higher than the grass/shrub sub-formation and are assessed as being 2 metres in height. Lower fuel loads and hazard scores are identified for Yetman DSF and Western Slopes DSF.

3.6.3 Grassywoodlands (GW)

a) Ecological characteristics

Grassy woodlands (GWs) are dominated by an open to sparse layer of eucalypts with crowns rarely touching (RFS, 2006). An important characteristic of these grassy woodlands is that the dominant trees are usually box species or river red gums although *Allocasuarina* and *Callitris* sp. may form sub-dominants (Keith, 2004). Trees are typically 15-35 metres high, although they may be lower in sub-alpine and exposed situations. The understorey may contain a diverse array of grass and herbs, with sparse if any shrubs (RFS, 2006). There are 7 GW classes within this formation identified by Keith (2004), however there are other semi-arid woodlands in areas of lower rainfall that lack the characteristic grassy understorey.

b) Regional distribution

The 7 GWs of NSW range across much of central NSW and are often dominated by Box eucalypt.

GWs are found on more fertile fine textured soils usually on flat to undulating terrain of the tablelands, western slopes and lower rainfall coastal lowlands. Rainfall is usually in the range of 500-900 mm annually and may be found near areas of forest, but lack the shrub layer diversity and cover of their forest counterparts (Keith, 2004).

GW are also found in the sub-alpine areas of the New England, Monaro and the Brindabella Ranges near Canberra as well as Kosciusko National Park.

c) Fuel characteristics

Structurally, there is generally a near surface layer and canopy, with a low elevated layer, which appears to blend in with the near surface layer (see Photo 3.3).

In the sub-alpine areas, fuel loads and hazard scores are higher those of the coast or tablelands and exceed 27 tonnes per hectare (total hazard score of 3.5) making them comparable to the DSFs.

Table 3.6 below identifies that most of the GWs have fuel loads of 18-20 tonnes per hectare and hazard scores ranging from 2.19 – 3.03.

Photo 3.3: Grassy woodlands showing significant fuel loads (photo by author)

Table 3.6: 25 year average fuel loads and hazard scores of NSW grassy woodland formation (derived from Watson et al 2012, UoW 2013)

Vegetation Class (Keith 2004)	25 year average Fuel Load (tonnes/Ha)					25 Year Fuel Hazard Score			
	Surface	Elevated	Bark	Canopy	Total	Surface	Elevated	Bark	Total
Coastal Valley GW	8.00	2.00	1.58	6.40	18.0	2.55	3.03	2.00	3.0
Sub-alpine GW	15.99	1.99	0.96	8.30	27.2	3.52	3.03	2.00	3.5
Tableland Clay GW	10.00	0.50	1.64	6.40	18.5	2.99	2.19	2.00	3.0
New England GW	10.00	0.50	3.30	6.40	20.0	2.99	2.19	3.00	3.6
Southern Tablelands GW	10.00	0.50	2.01	6.40	18.9	2.99	2.20	2.00	3.0
Western Slopes GW	10.00	0.50	1.33	6.40	18.2	2.99	2.19	1.00	2.2
Floodplain Transition GW	10.00	0.50	1.92	6.40	18.8	2.99	2.19	1.00	2.2

3.6.4 Rainforests.

a) Ecological characteristics

Rainforests have a continuous and closed canopy with interlocking branches restricting light penetration to the sparse understorey of soft ferns and herbs (RFS, 2006). Leaves are held horizontally on trees, vines and soft leaves shrubs. Vines and thickets may be present on trunks of trees which may exhibit buttressing (Keith, 2004). They occur mainly in areas which have soils of moderate to high fertility, are highly erodible with a strong organic layer at the surface and reliably moist. Fire is infrequent. Rainforests are frequently found in sheltered areas of the escarpment and coastal lowlands (Keith, 2004) but would have occupied a much larger range than at present but were subject to extensive clearing on flatter areas (e.g. near Kiama), low elevation floodplains on the north coast (e.g. Clarence and Hastings Rivers) and near coastal hills (e.g. the Big Scrub between Lismore and Byron Bay) for agriculture and timber getting (Keith, 2004).

b) Regional distributions.

There are 9 classes within the rainforests formation, although two, the Oceanic Rainforests and the Oceanic Cloud Rainforests are restricted to Lord Howe Island (Keith, 2004).

The remaining rainforest classes for NSW are:

- Subtropical Rainforests
- Northern Warm Temperate Rainforests
- Southern Warm Tropical Rainforests
- Cool Temperate Rainforests
- Dry Rainforests
- Western Vine Thickets
- Littoral Rainforests.

c) Fuel characteristics

The data from the University of Wollongong study (Watson et al, 2012) does not differentiate between rainforest classes within the formation and as such, only the one set of fuel load and hazard score values are applied across all classes.

It has been suggested (Watson et al, 2012; RFS, 2006) that the forest model of fire behaviour is appropriate for rainforest vegetation classes, however this should be treated with some caution. This is not to suggest that bushfires do not travel through rainforest communities.

Although found within the eastern parts of the State, it would not be suitable to assess fire behaviour using the comparison of FFDM5 and DEFFM, although the FFDM5 model has been used in the absence of any other models. Wildfires within rainforest areas can be observed (author's personal observations), however, they fall outside of the scope of the current study, due to their lower fire behaviour characteristics and complex fuel arrangements. Photo 3.4 illustrates a typical rainforest vegetation community.

Photo 3.4: Rainforest vegetation (Royal National Park) showing elevated fuel (photo by author)

Table 3.7 provides the 25 year average fuel loads and hazard scores for rainforests in NSW.

Table 3.7: 25 year average fuel loads and hazard scores of NSW rainforest formation (derived from Watson et al, 2012, UoW, 2013).

Vegetation Formation (Keith, 2004)	**25 year average Fuel Load (tonnes/Ha)**					**25 Year Fuel Hazard Score**			
	Surface	Elevated	Bark	Canopy	Total	Surface	Elevated	Bark	Total
All Rainforests	9.00	1.00	0.60	2.60	13.2	2.77	2.62	0.00	2.5

3.6.5 Heaths, scrubs and shrublands.

Heathlands are comprised of low to tall shrubs and are found on the coast and nearby mountain ranges on shallow sandy or infertile soils and have associations common with dry sclerophyll forests but lack the characteristic eucalypt trees associated with the shrubby sub-formations of dry sclerophyll forests (Keith, 2004). AS 3959-2009 refers to these classes as being divided between scrubs or shrublands dependent on height (SAA, 2009). Shrublands have shrub heights of less than 2 metres whereas scrubs have shrubs of about 2 metres or more (RFS, 2006) (SAA, 2009). Some mallee forms of trees may be found in heaths but should not be confused with the semi-arid woodlands or western mallee, which is often referred to as heath and scrub or the arid shrublands including the mulga of western NSW (Catchpole et al, 1998). Although the heathland communities are highly diverse, they are restricted in distribution.

There are seven classes within the heath formation (Keith, 2004). These are:

- Coastal Headland Heaths
- Wallum Sands Heaths
- Sydney Coastal Heath
- South Coast Heaths
- Northern Montane Heaths
- Sydney Montane Heaths
- Southern Montane Heaths

In addition to the heathlands, there are 6 classes within the freshwater wetlands formation which include two classes, the coastal heath swamps and the inland floodplain swamps, which have a diverse shrub layer character and can be treated as heathlands. As discussed in Chapter 2, this is due to the characteristic fire behaviour which does not rely on ground fuels for fire spread, the fuel being within the whole plant.

Although not part of the current study, fuel loads are dependent on height of vegetation and may reach approximately 35 tonnes per hectare (Watson, 2011).

3.6.6 Grasslands.

NSW native grasslands are dominated by tussock grasses with broad leaved herbs within the inter-tussock spaces and can be found over a wide range of environments from the coast to far western NSW (Keith, 2004). They are most often associated with deeper and more fertile soils (RFS, 2006). In addition, much of the woody vegetation within the landscape has given way to introduced grasslands used for grazing or grain production. In many areas, the remnants of these former timbered grassy woodland communities can be seen in the remaining isolated trees within the western slopes and tablelands of the State.

There are 5 classes of native grasslands within the grassland formation (Keith, 2004) and three classes of the freshwater wetlands formation that exhibit fire behaviour in line with the grassland models discussed in Chapter 2. Grasses may be perennial or annuals. These classes of grasslands are:

- Maritime Grasslands
- Temperate Montane Grassland
- Western Slopes Grasslands
- Riverine Plain Grasslands
- Semi-Arid Floodplain Grasslands

The grasslands and freshwater wetlands although important, do not form part of the current study.

3.6.7 Other formations and classes.

There are five (5) other formations worth noting for NSW native vegetation, although many fall outside the scope of the current study as they do not utilise the forest fire behaviour models central to the current study (AS3959, 2009).

These formations include the alpine complex (4 classes), saline wetlands (4 classes), arid shrublands (7 classes), forested wetlands (4 classes) and the semi-arid woodlands (13 classes) (Keith, 2004). The distribution of semi-arid woodlands in NSW is shown in Figure 3.8.

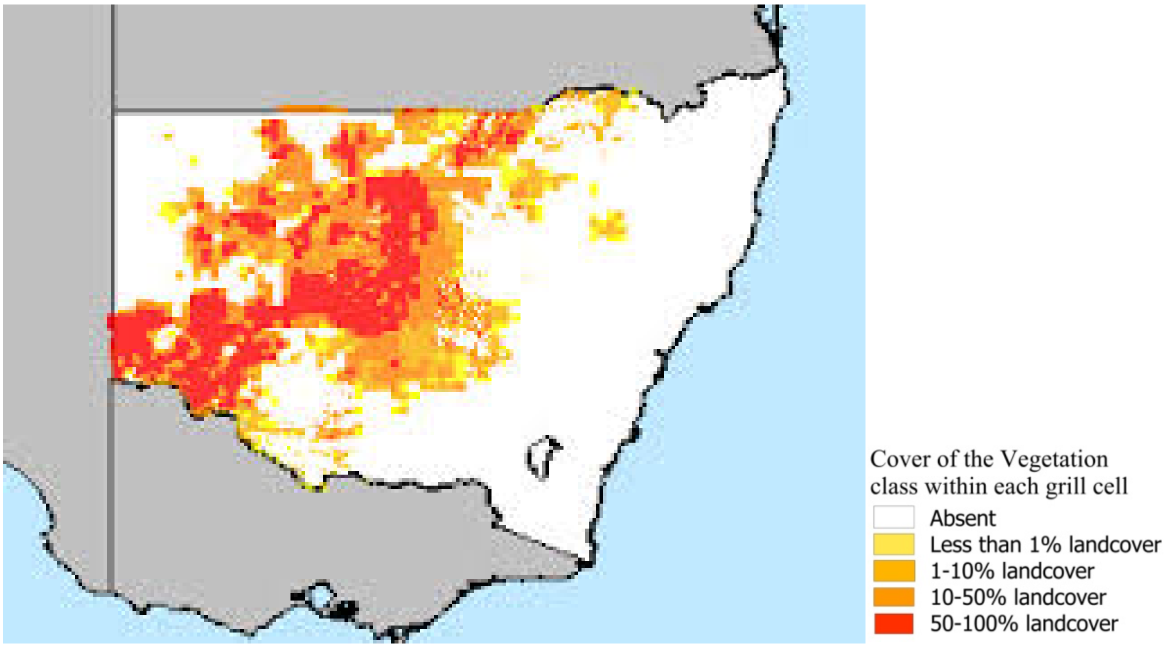


Figure 3.8: Distribution of semi-arid woodlands in NSW (source: NPWS, 2008)

Some of the semi-arid woodlands and forested wetlands do form part of the suite of vegetation which may exhibit fire behaviour in line with forest fire behaviour models (RFS, 2006), however as has been noted, at least some of the semi-arid woodlands (mallee) are considered to fall within the shrubland/scrub/heath fire behaviour models (SAA, 2009).

As discussed in section 2.4, the CSIRO Grasslands Meter for Northern Australia may be appropriate for some of the semi-arid woodlands, whereas the mallee-heath model by Cruz et al (2014) would be used for the mallee classes. In addition, there are a number of introduced plant communities, the most notable of which are blue gum and pine plantations. All of these vegetation classes fall outside the scope of the current study.

There are 4 classes of Forested Wetlands, which may be found along the coast or on inland waterways. These vegetation classes vary widely with the Coastal Swamp Forest having significantly high fuel loads when dry to the more grassy classes, associated with the Inland Riverine Forests. Although the forest fire behaviour models could be used for these vegetation classes, there is insufficient fuel data upon which to investigate the application of these models at this time.

3.7 Comparative Vegetation and Fuel Characteristics for Model Comparison

Watson (2011) undertaking a literature review has identified that a number of forest vegetation classes, exhibit similar characteristics in terms of fuel accumulation rates (see 3.3 above) and/or fuel loads at steady state conditions. It appears these extend to fuel structure (Watson, 2011). Additional literature reviews by the University of Wollongong (2013) also provides some considerations for canopy fuels, however, there is limited data on elevated fuel heights or near surface fuel heights (Watson et al, 2012), necessary for flame height calculations in Eq. 2.7. The similarities in vegetation fuel characteristics seen in Tables 3.4-3.7 allow for the development of examples which can be used within vegetation formations allowing these to be used for DEFFM fire behaviour calculations. Due to the nature of the reviews, there is little information on confidence or errors outside of the author's own PhD work on Cumberland vegetation (Watson and Morris, 2006).

There is a bias in some examples as Watson et al (2012) does not provide an extensive outline of near surface and elevated fuel heights, necessary for DEFFM calculations. Tables 3.4-3.7 provide the detailed fuel loads and hazard scores within each vegetation class for surface (and near surface), elevated and canopy fuels.

WSF grade into the Sub-alpine Woodlands (Keith, 2004). Fire behaviour (rate of forward spread and flame heights) for alpine vegetation classes can be expected to be higher than for other vegetation classes within their formations based on fuel loads and hazard scores (see Chapter 5 for details). There is a paucity of fuel load/structure information on Western Slopes DSFs and woodlands. Photographic images of elevated fuels for the Western Slopes DSF appears very low (<1m) (Keith, 2004). When considering fuel load/hazard scores, these images appear to show that the near surface and elevated components blend into each other. The Western Slopes Woodlands have no apparent elevated layer but a pronounced grassy near surface layer.

Table 3.8 below provides a summary of vegetation classes which exhibit similar fuel and structural components and the chosen example(s) for the particular group of vegetation. In general, some western and alpine vegetation classes have not been included in Table 3.8.

Table 3.8: Vegetation classes and fuel loads for structural elements within (sub-) formations to determine surrogate suitability in DEFFM calculations

Sub - formation	**Vegetation Classes in Group**	**Limit values of fuel load (Watson 2011) t/Ha**				**Examples of Group (Watson et al, 2012).**
		Litter	Litter/ NS	Elevated	Canopy	
WSF - shrubby	North Coast South Coast Northern Escarpment Southern Escarpment	17	19	3	10.1	North Coast
WSF - grassy	Northern Hinterland Southern Lowland Northern Tableland Southern Tableland	18	18	2	8.1-9.6	Northern Hinterland
WSF - grassy	Montane WSF	24	24	2	8	Not available
DSF Shrubby	Sydney Coastal Sydney Hinterland Sydney Montane North Coast Northern Escarpment	14.5	16.4	4.9	3.5	Sydney Coastal North Coast
DSF Shrubby	Coastal Dune South Coast Sands Sydney Sands Flat	17	18	2.5	8.4	Not available (similar to WSF shrubby)
DSF Shrubby	South-East Southern Wattle	10	12	5	7.6	South-East
DSF Shrubby (Yetman not included)	Southern Tablelands Northern Tablelands Western Slopes	19	20	2.5	5.8	Southern Tablelands
DSF – Grass/Shrub (Bark hazards vary widely within this sub-formation) Pilliga Outwash not included.	Clarence Hunter-Macleay Cumberland Southern Hinterland Northern Gorge Southern Gorge Central Gorge New England North-west Slopes[a] Upper Riverina	11.9	11.9	2	8.8	Hunter-Macleay Cumberland
GW (Western Slopes and Floodplain Transition not included)	Coastal Valley Tableland Clay New England Southern Tablelands	8	10	0.5-2	6.4	Coastal Valley
GW	Sub-alpine	16	16	2	8.3	Not available

a. referred to as a woodland but classified within DSF formations.

The Yetman DSF has not been included due to the limited extent and lack of details on elevated fuel heights, however, structurally has much in common with Cumberland DSF.

In the case of alpine vegetation classes (Montane WSF and Sub-alpine woodlands), fuel loads are higher than others within their formations, but are largely limited in extent to protected areas (Kosciusko National park) and surrounds and as such do not form areas generally available for development. At higher elevations, the Montane

Table 3.9 below, provides overall fuel parameters required for DEFFM and MacArthur models as well as default values provided by the CSIRO (2015) for dry sclerophyll forests (used in fire behaviour computer modelling).

Table 3.9: Overall fuel parameters for fire behaviour modelling for 9 NSW forest and woodland classes and CSIRO default values

Vegetation Class (Keith, 2004)	Hazard Score - surface	Hazard Score - near surface	Height - near surface (cm)	Hazard Score - (elevated)	Height - elevated (cm)	Weight - understorey (t/Ha)	Weight total (t/Ha)
North-coast WSF	3.8	3.4	33.2	3.0	254	25.6	35.7
Northern Hinterland WSF	3.65	3.4	38.1	3.0	254	23.3	32.9
North Coast DSF	3.7	3.7	38.6	3.0	226	24.5	28
Sydney Coastal DSF	3.5	3.4	31.6	3.5	280	23.5	27
South-east DSF	3.4	3.1	39.9	2.5	211	20.1	27.7
Southern tableland DSF	2.8	2.8	22.7	2.0	104	24.2	30
Hunter-Macleay DSF	3.2	3.4	29	2.7	233	15.7	24.5
Cumberland DSF	2.9	3.0	13.7	3.1	167	16.2	25
Coastal Valley GW	3.0	3.2	18	3.2	189	11.6	18
CSIRO DSF* (default)	3.5	3.0	25	-	-	25#	35#

* not used in the current study as not all values are available. # default from AS3959-2009.

The North-coast WSF is representative of the shrubby sub-formation of WSF whereas the Northern Hinterland WSF form part of the grassy sub-formation. Interestingly, the elevated fuel heights for both of these WSF classes are given as 254 cm (Watson et al, 2012) which appears high for the grassy sub-formations.

The Hunter-Macleay and Cumberland DSF classes form part of the grass/shrub sub-formation whereas the North-Coast, Sydney Coastal, South-east and Southern Tableland DSF classes form part of the shrubby sub-formation. These closely share many of the fuel load and hazard score characteristics within their respective sub-formations, with the Cumberland DSF being found within the Sydney FWD but appears to be representative of some of the western region vegetation classes, notably the Upper Riverina DSF.

The Coastal Valley Grassy Woodland class (CVGW) has been used as a representative GW class, although it has the lowest surface and near surface fuel characteristics (hazard score and fuel loads) of other GWs, and must be interpreted with care. It is clearly not suitable for higher elevations in the New England and Monaro-Alpine districts, where fuel loads and hazard scores are notably higher and are more likely to align with some of the grass/shrub Cumberland DSF. For both the New England and Alpine Monaro, the Cumberland DSF has been used in preference to the CVGW as representative of these woodland characteristics.

The CSIRO 'default values' were considered in comparison with the fuel and hazard scores but did not adequately provide for a vegetation class which could be used as a surrogate for other vegetation classes. As there is significant uncertainty in relation to elevated fuel heights and near surface fuel heights, it seems undesirable to use these data for the current study.

As such, the 9 vegetation classes are used as surrogates for other forest and grassy woodland vegetation classes, where there is currently insufficient information to apply the DEFFM equations. It is also assumed that hazard scores accurately reflect fuel load conditions, although this is far from certain.

3.8Summary

A major aim of this study is to provide a comparison of the two major fire behaviour models for forest fires in NSW, based on a common data set for fire weather.

Vegetation classes form the basis of fuel characteristics for use within these fire behaviour models (see Chapter 2). The vegetation of NSW can be described in terms of formations (and sub-formations), classes and communities.

Five (5) of the formations/sub-formations described in this chapter are suitable for comparative purposes (Watson, 2013), these being:

- Wet sclerophyll forests (shrubby) sub-formation (7 classes);
- Wet sclerophyll forests (grassy) sub-formation (2 classes);
- Dry sclerophyll forests (shrubby) sub-formation (14 classes);
- Dry sclerophyll forests (grass/shrub) sub-formation (11 classes); and
- Grassy woodlands formation (7 classes).

These five (sub) formations are all suitable for assessment and comparisons between the FFDM5 and DEFFM fire behaviour models. For each class within these formations, the fuel loads have been identified as have the hazard scores. However, the existing data for these classes do not provide for an extensive understanding of near-surface and elevated fuel heights. So as to address this limitation, certain vegetation classes have been used as surrogates for other classes within the (sub) formations, where these near-surface and elevated fuel heights have been determined. This is clearly an area of further research.

The current study has found that two WSFs are suitable surrogates for the WSF vegetation classes on the Coast and Tablelands, covering districts 1-11. Further, the study has also found that there is little point assessing WSF, DSF or GW vegetation for the Far Western parts of the State covered by District 19-21. Districts 19-21 form the rangelands of the State and are better served by mallee-heath and grassland models and so fall outside the scope of the current investigation. WSF are not found within districts 12-18.

The DSF are widely distributed in the remainder of the State, and although six DSF and one GW vegetation classes have been used as surrogates for all classes, there are some gaps, notably in the Western Slopes, the higher elevations associated with the montane forests, and the grassy woodlands west of the coastal areas.

Within the other formations (notably rainforests and forested wetlands) there are some classes which may provide some improved basis of fire behaviour determination based on forest fire behaviour models, although the suitability of such models to these vegetation classes is unknown. The absence of data on hazard scores and/or near-surface and elevated fuel heights combined with the uncertainty of fire behaviour model suitability means that these additional vegetation classes fall outside the scope of the current study.

Heath models rely on wind speed as do grassland models (Cheney and Sullivan, 2008), although one of the grassland fire behaviour models also incorporates a Grassland Fire Danger Index (Purton, 1982). Semi-arid woodlands and arid shrublands provide only limited ability for comparison, as these are better described by shrubland fire behaviour (Catchpole et al, 1998), especially the mallee and mulga classes.

Future work on these and other classes would be possible but also fall outside of the scope of the present research.

CHAPTER 4 - CLIMATE, CLIMATE CHANGE AND FIRE WEATHER IN SOUTH-EAST AUSTRALIA

4.1 Introduction

Bushfires vary across the landscape both temporally and spatially. The temporal aspects of bushfires are determined by seasonal weather change and the longer term local as well as global climate. The spatial extent of fires is influenced by the presence (or absence) of fuel which, in turn, is also influenced by weather and climate. Whereas forecasting the weather patterns of the near term relies on understanding the instability of current weather patterns, the prediction of the characteristic climate relies on long term patterns of weather, typically over at least 30 years of observed data as suggested by Lindsay (2003).

Factors such as wind, temperature and humidity at the time of fire are considered ‘ambient drivers’ of fire size and intensity, whereas drought is a ‘preconditioning driver’ of longer term influence over fire activity, including frequency of fire (Bradstock et al, 2009) and has been discussed in Chapter 2.

At the *extremes*, large infrequent fires are often investigated so as to improve the forecasting capability of weather models and the prediction of these types of fire events (Mills, 2009). Post fire investigations of extreme weather events associated with large fires such as Hobart fires (1967), Ash Wednesday (1983), Dandenong fires (1997), ACT fires (2003), Eyre peninsular (2005) and Black Saturday (2009) have given us insights into underlying drivers of fire events through studies of mesoscale meteorology (Sullivan, 2004; Mills, 2009; Parkyn et al, 2010). Such investigations are not restricted to Australia. Similar investigations have been reported in Europe (Gomez-Tejedor et al, 1999), the US (Crimmins, 2006; Crimmins and Comrie, 2004) and Canada (Amiro, et al 2004; Beverly and Martell, 2005). Increasingly however, the focus has moved to consider the implications of climate change on bushfire behaviour (Moriondo et al, 2006) and suppression (Fried et al 2008), fire occurrence (Wotton et al, 2010; Williams et al, 2001), area burnt, bushfire seasonal shifts (Clarke et al, 2011) and fire frequency and severity at the global scale (Oliveras et al, 2009; Meyn et al, 2007; Flannigan et al, 2009).

The relationships between fire events and weather (Boer et al, 2008; Viegas, 1998) and between fire behaviour and weather have been well established in the literature (Sullivan et al, 2012). The relationship of fire events with climate change suggests highly variable patterns of fire weather (Keeley and Syphard, 2016). A study of the climatology of SEVERE -EXTREME fire weather days in Victoria (Long, 2006) focused on the frequency and synoptic wind patterns associated with such extreme events. The study examined 29 years of historical daily data at 15:00 hr and confirmed the significance of the northerly and westerly synoptic wind patterns associated with adverse fire weather days, though the influence of a subsequent south-easterly cold front was not considered as pointed out by Hasson et al (2008).

Finkele et al (2006) have developed a 40 year (1965-2005) gridded (25km grid) daily drought factor for forecasting FFDI determination in Victoria and for comparing with both KBDI and SDI indices. While both approaches have limitations, KBDI delivers a more gradual drought factor than SDI which is related to evapo-transpiration rather than infiltration.

In effect, all parts of continental Australia can experience bushfire events; however, the risks associated with such events can vary with seasons of greatest rainfall and temperature regimes (Hasson et al, 2008). There is a fire season somewhere in Australia at any time.

At the global scale, the influence of the El-Nino Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) are also important drivers of local fire weather conditions (Cai et al, 2009; Williams and Karoly, 1999; Verdon et al, 2004; and Ferguson, 2001).

4.2 Climatic Conditions and Trends

4.2.1 Climatic classification (geographical aspects)

The climatic classification system (referred to as the Köppen classification scheme) combines temperature and rainfall and the associated native vegetation (Sullivan et al, 2012). NSW is dominated by the temperate nature of climate (rainfall and temperature ranges) and vegetation types. In particular, New South Wales’ vegetation formations are dominated by forests in the east, woodlands more centrally and arid shrublands to the west (Sullivan et al, 2013). The biogeographic model of Murphy et al (2012) has in many respects, advanced upon this system.

Northern Australia is strongly influenced by the tropical monsoon season which brings substantial rain and tropical cyclones with dry and moderate winters (Lindsay, 2003; Sullivan et al, 2012).

Figure 4.1 illustrates the detailed Australian Climate Classification which distinguishes between Temperate, Equatorial, Tropical, Sub-Tropical, Desert and Grassland environments. It can be seen in Figure 4.1 that the temperate areas of NSW are strongly associated with the distribution of forests and woodlands identified in Chapter 3.

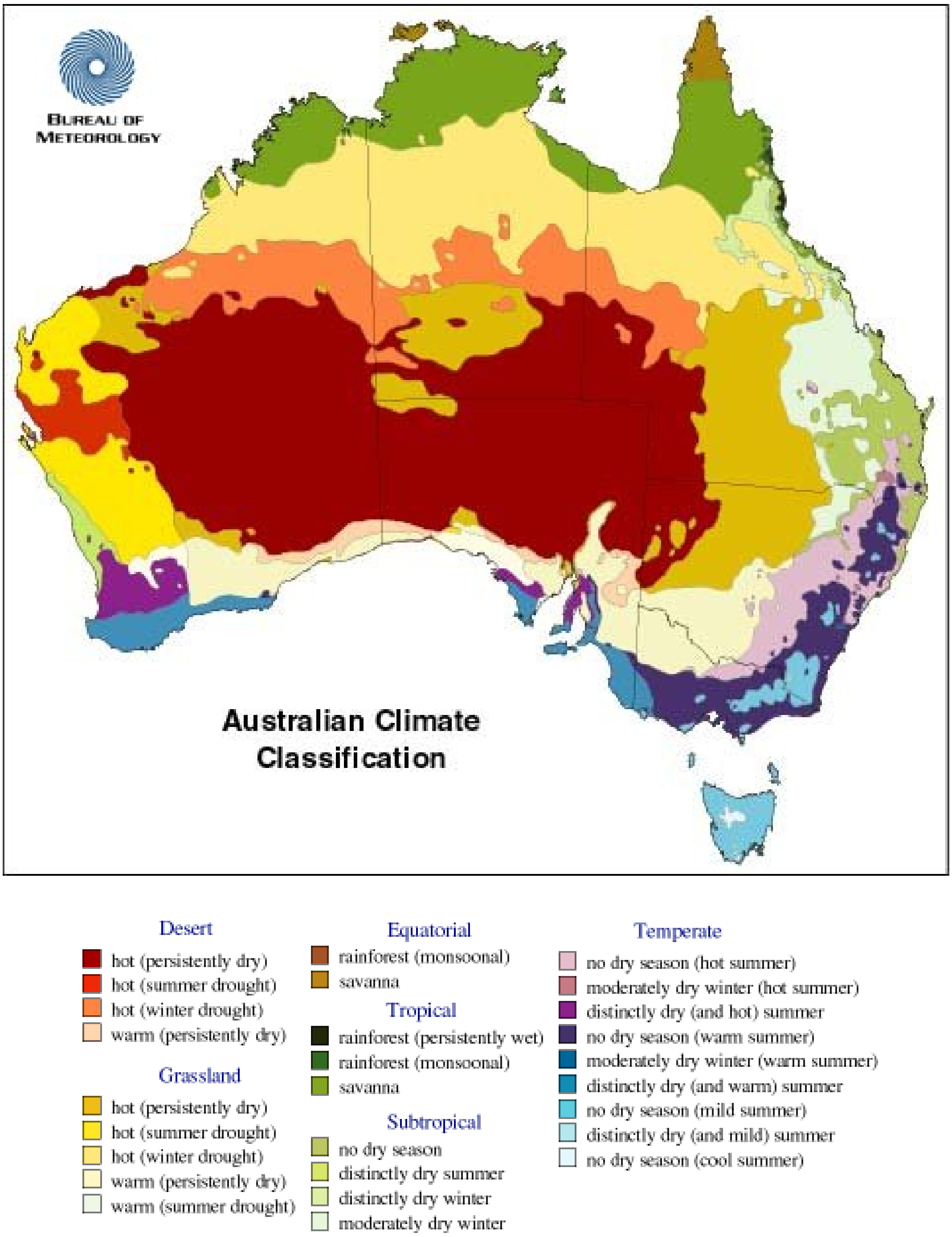


Figure 4.1: Australian Climate Classification (Köppen), (BoM, website 2009)

The grassland areas of western NSW transition from the woodland areas of Central NSW, whose understoreys are dominated by grasses, to the desert areas of north-east NSW including the western mallee near Cobar.

This system is useful in illustrating the relationship of vegetation to geographical areas and that vegetation is also a reflection of climate. It is widely used by climatologists and geographers although some modification from the original Köppen system has been developed (Stern et al, 2000).

4.2.2 Bushfire seasons

Although the Köppen system is a useful classification that reflects climate and associated vegetation, this geographic context and latitudinal associations do not fully reflect the development of changes in bush fire seasons which is related more to seasonal changes than latitude and annual rainfall.

Although bushfires are regular occurrences in the landscape, their timing is related to periods of low soil moisture, high temperatures and reduced humidity. Periods of dry and wet seasons progress over the continent from north to south.

Figure 4.2 shows the spatial and temporal aspects of the broad inter-annual fire seasons (Lindesay, 2003) across the Australian continent, with Northern Australia dominated by the monsoon (wet) periods followed by the dry period during which time the savannah grasslands cure and readily burn.

In Southern Australia, the fire season occurs over the hotter summer periods with rainfall falling predominantly in winter and spring, although this can be highly variable (Sullivan et al, 2012).

Figure 4.2 indicates three different bushfire periods within NSW. It is generally accepted that fire season starts in the north of the State (historically in late September) and migrates progressively towards the south with time and with major fires occurring around January and February.

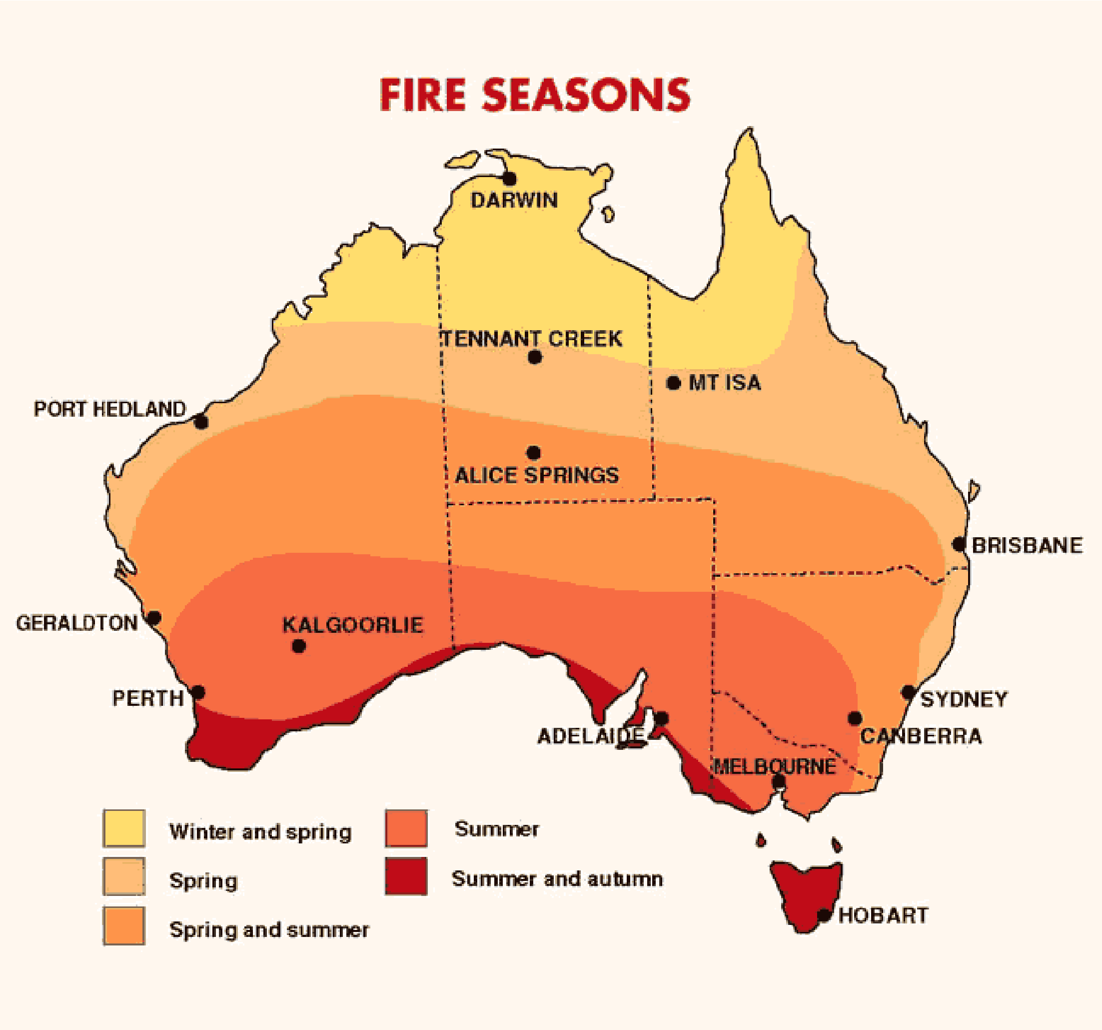


Figure 4.2: Bushfire Seasons in Australia (Bureau of Meteorology website)

Studies in the USA and Australia suggest that under higher CO_2 emission scenarios that fire season conditions will lengthen (Westerling et al, 2006; Hennessey et al, 2011 and Hennessey et al, 2005). This is discussed further in section 4.3 below.

However, the difficulty arises that fire seasons in SE Australia are largely based on administrative decisions for the control of ignition sources (through the issuing of permits to light fires) and are not directly related to a specific fire weather conditions (*Rural Fires Act 1997*). In NSW, the administrative bushfire danger period (season) is the period 1 October to 31 March (see NSW RFS website). A more rigorous and scientific basis of determining regional fire seasons based on fire weather risk has not been developed for the implementation of these administrative arrangements.

Analysis of prevailing weather giving rise to adverse fire weather conditions may provide some valuable insights as to the influence of FFDI on house losses. Blanchi et al (2010), identified that where FFDIs increase there is a corresponding increase in potential house losses, notably where FFDI>40. Clarke et al (2011) noted that there are shifts in the frequency and seasonal timing of FFDI 40 or greater, and notes a trend towards an earlier seasonal onset of these FFDIs. However, this threshold value is not the rationale for the administrative determination for a fire season, which relates more to broader fire management and fire escape and control (*Rural Fires Act 1997*). Blanchi et al (2010) identified FFDI=40 as the point beyond which extensive loss of houses may occur. This was also identified by Bradstock et al (1998) as being a likely tipping point for house loss and property protection. The use of FFDI=40 would therefore be inappropriate having regard to the likely fire behaviour between FFDI=25 (HIGH) and 40 (which is almost at EXTREME).

Bateman (2007) considered a more realistic scenario in which he identified changes in the percentage of days of FFDI>14 (under the pre-2009 fire danger ratings) as an expression of fire risk (i.e. at a level of FFDR of High or greater), and within the context of ENSO periods. Currently, FFDI of 12 is considered most appropriate for limitations on prescribed burning (NSW RFS, 2009b) due to the danger of fire escape and management. As such the onset of successive days of FFDI of 12 or above maybe a better reflection of fire season in Figure 4.2 than that FFDI of 40 or above. In contrast, Hennessey et al (2005) identified that the frequency of seasonal FFDI$\geq$25 was a more appropriate approach.

Internationally, the significance of global warming and wildland (bush) fire in the western USA was highlighted by Westerling et al (2006). This study revealed the earlier onset of spring forest fires since 1970 with the increased frequency of large fires, longer fire durations and longer fire seasons. Modelling of impact of climate change on wildland fire and suppression had also been considered in the USA under doubling of atmospheric carbon dioxide (CO_2) scenarios (Fried et al, 2004) and predicted that there would be an increase in severe wildland fires which could not be suppressed using initial attack. A study of Alberta Boreal forests using the Canadian fire danger rating system, also modelled increased CO_2 which resulted in increased burn area (Tymstra et al, 2005). Similar studies in Australia had identified that seasonal cumulative FFDI ($\sum$FFDI) (Hennessey et al, 2005) is most sensitive to temperature changes under a doubling of CO_2 levels, and that other than Hobart (Tasmania) and Katanning areas (South Western

Australia) the fire season has been getting longer across the remainder of Australia (Williams et al, 2001).

4.2.3 Temperature and humidity

In addition to the seasonal bushfire conditions, it is important to also consider how temperatures and humidity give rise to climatic conditions which will support bushfire events. Indeed, it is generally recognised that bushfire events in Northern Australia do not occur under the same climatic conditions as elsewhere in the lower parts of the continent.

To address this more carefully, we need to consider the role of temperature and humidity in Figure 4.3 in addition to seasonal rainfall (Bureau of Meteorology website, 2009). This map is based on data between 1961 and 1990.

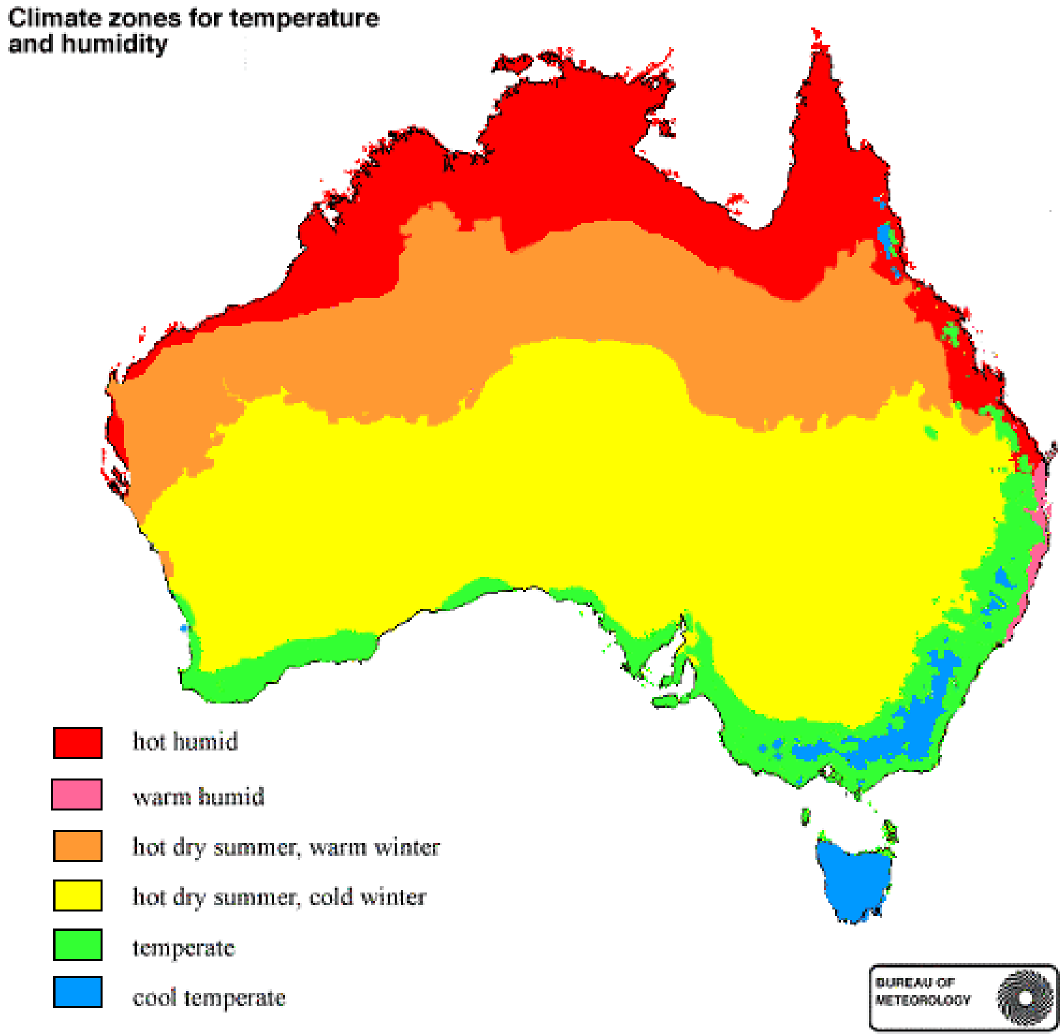


Figure 4.3: Climate zones for temperature and humidity (Bureau of Meteorology website)

It can be observed that temperate conditions prevail over the coastal areas with hot dry summers and cold winters further inland. Higher altitudes of the Australian Alps (e.g. Brindabella range and Kosciusko main range) and most of Tasmania are described as cool temperate.

The influence of temperature and humidity give rise to conditions which are conducive to the vigorous growth of vegetation in the form of forests and shrubland (heaths) close to the coast and higher elevation, with more grassy and woodland environments inland (Lucas, 2007). It also has the potential to reflect soil moisture which is important for bushfire behaviour (through fuel moisture, see Chapter 2).

A study of temperature variations for south-eastern Australia, showed that over the record (1860-2011), that there was only a weak correlation between with the Inter-decadal Pacific Oscillation and ENSO, and that temperature fluctuations had a stronger correlation for climate change with a confirmed rise of 1.1 degrees Celsius in maximum temperatures and 0.9 degrees Celsius for minimum temperatures since 1960 (Ashcroft et al, 2012). In contrast, Crompton et al (2010) suggested that losses arising from bushfire events were related to social factors and ENSO/IOD and not detected in relation to the climate change signal.As such, past studies are conflicting in relation to ENSO (and/or IOD) and the role of climate changes which is still uncertain.

At the diurnal level, temperature and humidity have an inverse relationship, such that as temperature rises, relative humidity drops. This relationship can be observed in Figure 4.4, which is the plot of temperature and humidity for the 7-9 January, 2013.

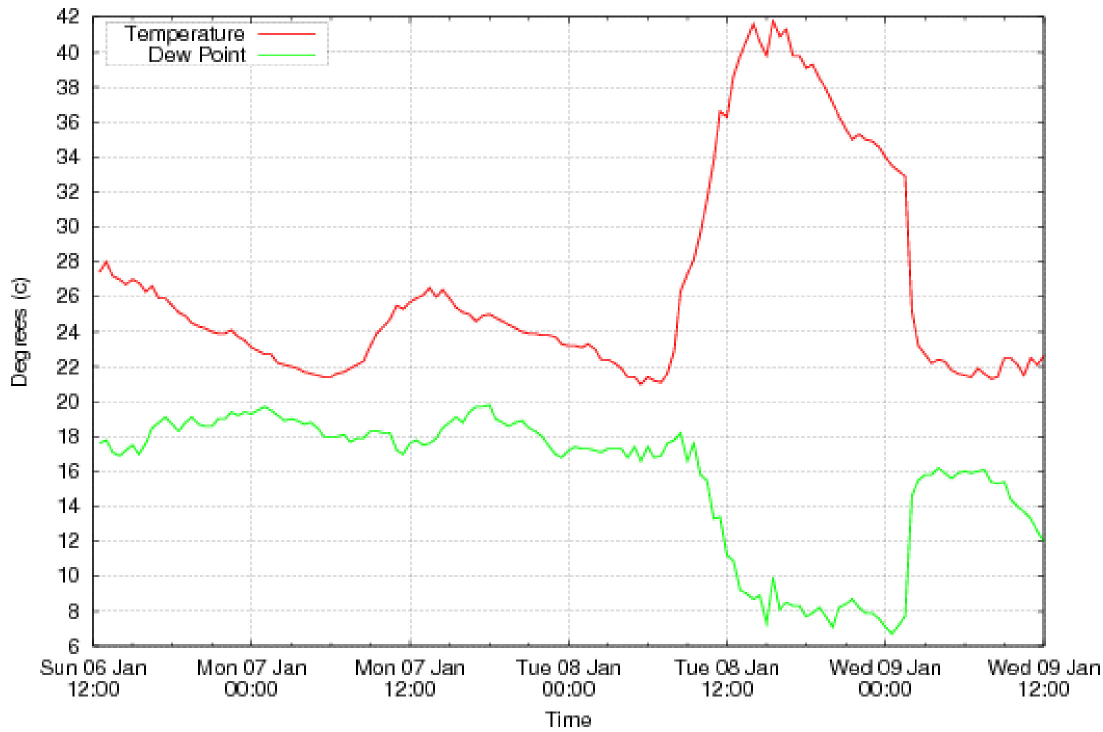


Figure 4.4: Diurnal variations in temperature and humidity example (BoM website)

Studies of temperatures have often focussed on percentile values (deciles) of probability distributions (Tencer and Rusticucci, 2009). In contrast, *extreme* value methods (Coles, 2004) have been applied to Australian temperature conditions since the 1970s (Dury, 1972).

In considering *extreme* temperature projections, different methods can be used (Oliveras et al, 2009). They can be grouped in terms of trend extrapolation, climatic modelling, mean changes (or decile scaling), *extreme value analysis* (using GEV), and other downscaling techniques (Hennessey et al, 2011).

Alexander et al (2007), used a dataset for Australia available from 1957 to 2005 and found that trends in extreme indices and for means for both temperature and precipitation are correlated, although the trends in temperature extremes are larger. For temperatures, mean minimum extremes are rising faster than mean maximum extremes, however, in summer maximum temperatures are rising at a faster rate.

A study of the likely effects of urbanisation showed that although urban weather stations showed that the effects of urbanisation 'heat island' effects increased mean and extreme temperatures (99 percentiles) and reduced variation between the two, but overall, there were significant changes in temperature independent of urban status (Chambers and Griffith, 2008). These extreme temperature changes were seen to be affected by major climatic features including ENSO, however, changes in temperature extremes were larger and had greater divergence from the mean.

At a local and sub-regional level, a study of Sydney showed that there was significant variation in extremes (90 percentile) of temperature and humidity between eastern and western Sydney. Humidity is higher near the coast, whereas heat waves are more likely further inland (Pepler and Rakich, 2010).

4.2.4 Seasonal rainfall

Where climate is described in terms of seasonal rainfall variation, then Figure 4.4 illustrates the present climatic zones. The Hunter, Greater Sydney, Illawarra/South Coast and Central West areas of NSW (identified in green in Figure 4.4) have more uniform rainfall over their geographical range, but are subject to major fluctuations arising from periodic events such as the El Nino/Southern Oscillation (ENSO) (Verdon et al, 2004). The onset of summer rains usually brings an end to the fire season in the north, whereas rain conditions progressively migrate south for the winter periods.

Figure 4.5: Major Seasonal Rainfall zones in Australia (BoM website)

There is a strong negative correlation between precipitation (rainfall events) and temperature in all seasons (Nicholls, 2012). The spatial variability for rainfall is greater than for temperature; however, a pattern of statistically significant decreases in extreme rainfall pattern has emerged in eastern Australia for the December to August period (Alexander et al, 2012).

In NSW, overall total rainfall has decreased since 1950 with a high variability from year to year, although mainly confined to winter and spring. In summer, the coastal and north-eastern rainfall tends to increase, whereas, the rainfall in the north-west tends to decrease (Hennessey et al, 2004).

Nicholls (2012) identified that since the 1970s, mean annual maximum temperatures are closely related to rainfall variations, however, the effect of warming has been larger than expected from the rainfall data. The conclusion of this study was that climate change, arising from anthropocentric greenhouse emissions was the most likely explanation, with drought exacerbating warming.

4.2.5 Wind, atmospheric instability and bushfire

It can be seen from the above discussion that the interaction of temperature, relative humidity and solar radiation (temperature) determines the drying of fine fuels and hence fire season (Moon et al, 2013). This drying effect can control the short-term fuel moisture content with higher temperatures, lower humidity, increased solar radiation (associated with summer) and aspect giving rise to lower fuel moisture (Sullivan et al, 2012).

It is interesting to note however, that neither wind speed nor direction plays a significant role in deriving fuel moisture, although wind speed forms a crucial aspect of FFDI and GFDI and bushfire behaviour more generally(see Chapter 2). The role of wind direction however is of crucial significance in that some correlations have been found between the parameter that are directly involved in FFDI evaluation and wind direction. For example, hotter dryer winds are usually driven from the north to westerly directions in south-east Australia during typical fire days (or high FFDI days) (see Speer et al, 2001; Webb et al, 2003; and Long, 2006). For DEFFM, wind speed is a crucial aspect of determining rates of spread and flame height (see section 2.3.2).

An appropriate system of describing 50 synoptic types for various wind speed and directions is given in a study of Victorian locations by Long (2006). This study utilised 16 wind directions, 4 flow strengths and is influenced by regional cyclonic or anti-cyclonic conditions in determining ‘EXTREME fire weather days’ (EFWD). EFWD are when the FFDI or GFDI exceeds a rating of 50. The results of the Long study (2006) also indicate that the EFWD conditions tended to occur between 12:00 hrs and 15:00 hrs local time, although they may on occasions continue to peak after that time (VBRC, 2010). It is noted that FFDI is independent of wind direction [see Eq. (2.1)].

Importantly, nearly 72% of EXTREME fire weather days (for both FFDI and GFDI) recorded at Melbourne Airport was from the direction of north, followed by 9% from the NNW, 7% from the NW and 3.2% from the WNW. No EFWD’s were recorded from the directions of E, ENE, ESE, SSE, SSW, with only small percentages (i.e. less than 1% each) from all other directions (Long, 2006). There has been no similar study in NSW, although there are likely to be similar conditions for New South Wales based on limited studies of Sydney fires (Speer et al, 2001) with the N-NW-W sectors likely to dominate in terms of NSW fire weather, with a subsequent onset of a cold front from the south and south-west (Mills, 2009; Lucas et al, 2007).

It is worth noting that atmospheric stability is also an important factor in Australia and can be expressed with an index range of 2 – 6, referred to as the Haines Index (Potter et al, 2008). The Haines index is a parameter for above ground stability and moisture. The Haines Index is intended to measure the potential for plume dominated or convective fires with increasing atmospheric instability (McCaw et al, 2007).

In Victoria, EXTREME fire weather days (>FFDI 50) were strongly correlated with increasing Haines Index, although a higher Haines Index did occur more frequently than just EXTREME fire weather day (Long, 2006). To date, there have not been any comparable studies of the Haines Index, although the conditions for higher Haines Index and FFDI are likely for NSW as in Victoria (Louis, 2014). The consideration of the Haines Index falls outside the scope of the current study, however, is an important aspect of fire weather, not addressed in the current FFDI calculations.

4.2.6 Southern oscillation index (SOI), Indian ocean dipole (IOD) and drought

Climatic variation across Australia is not simply a narrow band of weather parameters on an annual basis, but can vary dramatically across multi-decadal and inter-decadal global weather patterns, such as the Inter-decadal Pacific Oscillation (IPO) associated with SOI events (Verdon et al, 2004).

A significant amount of work has been undertaken to understand these phenomena, most notably the role of the SOI and IOD events as it impacts on drought. Verdon et al (2004) have noted that the SOI can have a significant effect on precipitation and temperature and hence drought conditions.

SOI is a measure of the difference in the atmospheric mean sea level pressure (MSLP) between Tahiti and Darwin and is determined using the system adopted by Troup and influences global and regional climate (Williams and Karoly, 1999). The presence of a stronger negative (-ve) gives rise to the El-Nino Southern Oscillation phase referred to as ENSO in which a lower pressure system can be found over Tahiti relative to Darwin. The reverse is true during La-Nina conditions. This has led to a number of Australian studies on the role that ENSO plays in both drought and fire weather conditions (Speer, 2009; Waskco and Sharma, 2009; Williams and Karoly, 1999; Campbell et al, 2009; and Verdon et al, 2004).

Figure 4.6 illustrates a typical pattern of El Nino or –ve SOI in eastern and northern Australia.

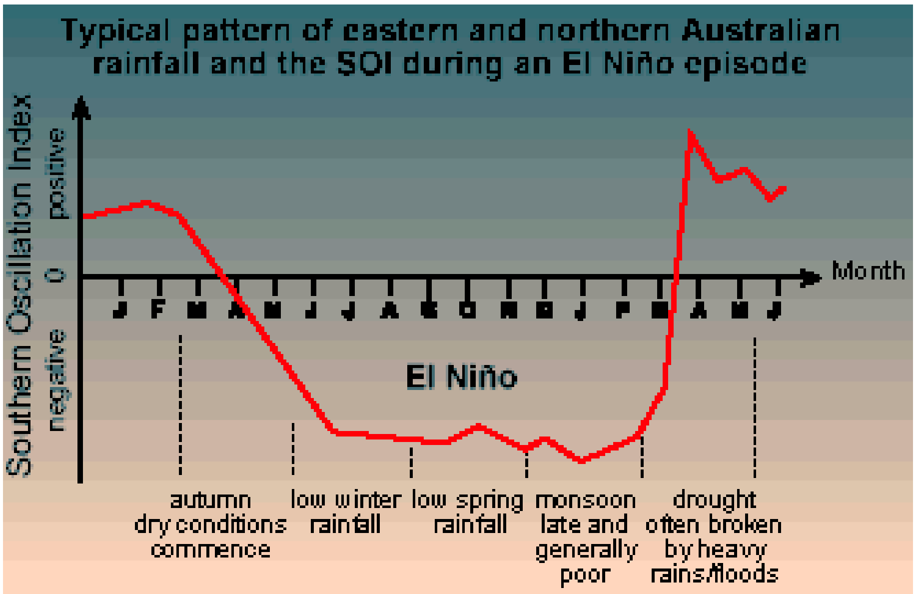


Figure 4.6: Pattern of SOI during El-Nino in eastern and Northern Australia (BoM website)

Studies are not solely restricted to Australia, with studies in Eastern Oregon and Washington (Ferguson, 2001), Alaska (Hess et al, 2001) and Utah (Brown et al, 2008).In the USA, and Argentina (Tencer and Rusticucci, 2009) the SOI exhibits increases in temperatures affecting cold and warm extremes and wildfire behaviour.

The pattern in SOI may explain the underlying trend for drought. Likewise, the IOD may be associated with drier conditions which may also explain associated in drought. The strength of the SOI and rainfall is usually associated with a summer pattern and hence summer average SOIs are used as a measure of SOI impact.

Where the pattern of SOI is trending relatively flat, then an increase in average FFDI may be attributed to climate change rather than SOI. However, the long-term rain deficiency in NSW and SE Australia more generally (Timbal, 2009) and extreme temperatures since 1996 are aligned more to climate change than the SOI or ENSO specifically (Hennessey et al, 2011). Relative humidity appears to be significantly lower during ENSO events and as such gives rise to higher seasonal FFDI with more days in the >50 FFDI distribution (Williams and Karoly, 1999).

Table 4.1 provides a summary of the DJF average SOI for years subject to ENSO events. Conversely, the average seasonal IOD is associated with winter (starting May or June) and spring (peaking August to October) patterns of rainfall or rainfall deficit (White et al, 2014).

Table 4.1: Average summer (DJF) SOI values for ENSO years (BoM website)

Year	Average SOI	Year	Average SOI
1905/06	-8.0	**1972/73***	-9.5
1914/15	-8.4	**1977/78***	-12.7
1940/41	-18.2	**1982/83***	-28.4
1941/42*	-8.4	**1991/92***	-17.1
1946/47*	-4.8	**1994/95**	-6.1
1965/66	-4.8	**1997/98***	-17.3

* Also years with concurrent positive IOD.

Other indicators, such as annual or 5 month running mean (moving average) of spatially average surface sea temperature anomalies can be used (Crompton et al, 2010).

Notwithstanding the potential importance of the SOI and ENSO cycle in extreme fire weather, studies of the Ash Wednesday (1983) and Black Saturday (2009) bushfires in Victoria show both were preceded by the onset of a positive IOD (Cai et al, 2009). The positive IOD generally peaks in spring and has a delayed impact on soil moisture for summer. It is rare for IOD events to be successive, hence are unlikely to lead to multi-year drought. The occurrence of IOD is independent of ENSO (Ummenhofer et al, 2009).

The most severe periods of drought are associated with the convergence of the ENSO and positive IOD however both are important for inter-annual drought events rather than inter-decadal events which are more likely to be associated with positive IOD in SE Australia (Ummenhofer et al, 2011). As such, the positive IOD appears to be a more pre-conditioning impact factor than ENSO (Cai et al, 2009; Ummenhofer et al, 2011). Table 4.2 shows recent years with convergence of positive IOD and negative SOI.

Table 4.2 Recent Years of convergence between IOD and ENSO (source: BoM, 2017).

		Year								
IOD Years	Neg.	1960	1964	1974	1981	1989	1992	1996	1998	2010
	Pos.	1961	1963	1972	1982	1983	1994	1997	2006	2012

La Nina   El Nino   Neutral SOI

4.3 ∑FFDI and Climate Change

The implications of climate change on forest fire behaviour has been gaining increasing attention, notably in the Northern Hemisphere (Westerling et al, 2006; Stocks et al, 1998; Nitschkeand Innes, 2008). More recently, Keeley and Syphard (2016) have identified that the impacts of climate change in the USA can vary in spatial and temporal scales, although Bradstock (2010) notes that not all impacts are attributed to climate change, but also factors such as increased CO_2 leading to increased biomass, and increase ignitions from population densities and land-use.

Since the 1950s, Australia has warmed by 0.85°C annually, rainfall has decreased in the SE, droughts have become deeper and the number of *extreme* days has risen (Hennessey et al, 2005). However, such changes are not uniform across the continent with higher rainfalls in north-west and central Australia (CSIRO, 2007).

A climate change study for changes in FFDI in 2005 covered 17 sites in NSW, Victoria, ACT and Tasmania (Hennessey et al, 2005). This study considered 30 years of historical data (1974-2004) of maximum temperature, precipitation, 15:00 hr relative humidity and wind speed. This study found that, compared to the 1974-2004 period, the modelled FFDI (and GFDI) using GCMs with two climate change scenarios (IPCC, 2001) in the two years of 2020 and 2050, showed changes of higher frequencies in FFDIs at the VERY

HIGH(>24-50) and EXTREME (>50) ranges in NSW, Victoria and ACT. However, FFDIs in Tasmania and the Australian Alps were largely unaffected with increased temperatures being offset by higher humidity.

A follow up of the 2005 study was conducted by Lucas et al (2007) with additional sites and inclusion of the 2006-07 fire season data (as the base years). This study used the output of an atmosphere only regional climate model rather than GCM to estimate the FFDIs for the new fire danger categories ratings (see Table 2.1) of EXTREME ($75 < FFDI \leq 100$) and Catastrophic (FFDI>100). It confirmed the modelled increase in frequencies in fire danger estimates (and as ∑FFDI) and changes to projected fire season lengths under the (then) latest IPCC report scenarios for CO_2 emissions (IPCC, 2007). The study by Lucas et al (2007) reported that there had been recent upswings in EXTREME and CATASTROPHIC days within the historical record and that their projections may be conservative and that the base case is already exhibiting evidence of anthropogenic climate change, which could influence fire seasons and the frequency of extreme events.

At the regional scale, another NSW study produced a preliminary assessment of climate change on overall weather conditions (temperature, rainfall, moisture balance) based on the 2001 IPCC findings (Hennessey et al, 2004). This study found that there was a tendency for recent (2003) dry periods to be warmer than in the past (1950) suggesting that recent droughts are exacerbated by higher temperatures and increased evaporation and water demand; and that there were decreases in annual intensity and frequency of daily rainfall extremes. This was consistent with an overall decline in rainfall since 1950 (Hennessey, 2004a).

The strongest declines in rainfall occurred in coastal locations, although the greatest changes in fire danger occurred inland.

A second study of 12 sites for NSW (Hennessey et al, 2004) used GCM and considered *extreme* conditions of temperatures (both average number of days $<0^0$C and $>35^0$C), drought, rainfall, winds and storm surges for future CO_2 scenarios. This study introduced concepts of return periods, however much of the work was based on frequency assessments without any *extreme* return period assessment. Unfortunately, this study provides little assessment of bushfire impacts, but notes that drought conditions will tend higher (increasing KBDI) in forthcoming decades over all seasons.

Table 4.3 sets out a summary of key finding for NSW climatic change conditions.

Table 4.3: Summary of changes in climatic conditions for NSW 1950-2003 (Hennessey et al, 2004)

Climatic condition (parameter)	Change in condition	Record (years)
Annual Mean Maximum Temperature Rise	0.15 °C/decade	1950-2003
Annual Mean Minimum Temperature Rise.	0.19^0C/decade	1950-2003
Increase in number of hot days (>35^0C)	0.10 days / year	1950-2003
Increase in # hot nights (>20^0C)	0.26 nights/year	1950-2003
Decrease in cold days (<15^0C)	0.22 days /year	1950-2003
Decrease in cold nights (<5^0C)	0.29 nights/year	1950-2003
NSW Annual total rainfall decrease	14.3 mm/decade	1950-2003
Mean relative sea-level rise	1.2mm/year	1920-2000
Increase in frequency of *extreme* sea level events (>2.1 m/year)	200%	1950 cf 2003.

By comparison, subsequent work on EXTREME events in Victoria (Hasson et al, 2008), including bushfire, has refined these studies with re-analysis techniques for historical weather data and improved projections. This study noted that FFDI had ‘considerable value’ when used for the assessment of seasonal characteristics.

Using regional atmospheric modelling system (RAMS) rather than GCM to calculate FFDI, Clarke et al (2011) projected increases in FFDI for the period to 2050 and 2100 using IPCC (2006) scenarios for four regions in SE Australia. The study found a range of responses to fire weather conditions and fire seasons. This built on an earlier RAMS study by Pitman et al (2007) which predicted increased risks of forest (and woodland) and grass fires potential under increased CO_2 emission scenarios. Although differing climate models are consistent in projecting larger scale warming, the study by Pittman et al (2007) noted that climate models may differ in their projection of precipitation changes and that a limitation of the climate models is that they are better at simulating large scale mean climate rather than evaluating the *extremes*. As a result of these limitations, this study found that the 95^{th} percentiles using the RAMS model were lower than those associated with high risk fire weather. However, such observations may not be associated with interpretations but rather with output expectations, since subsequent studies have shown that the 95^{th} percentile values would not exceed FFDI=40 over long term historical summer periods (DJF) for NSW weather station sites (Douglas, 2012; Douglas et al, 2014).

Further studies, including the trend in the annual 90th percentile of FFDI in the historical record 1973-2010 (see Lucas, 2010) showed an increase in the 38 Australian weather stations studied, with 24 of these being reported as significant increases and no weather station showing a decline (Clarke et al, 2012). Of these weather stations studies, the greatest increases were in the south-east Australia with greater increases in inland areas rather than the coast.

In considering all the above studies, it would appear that there can be anticipated increase in the frequency of fire weather conditions, and that drought may be an important factor. It is unclear from the studies of Hennessey et al (2005) and Lucas et al (2007) whether the major drivers for increased ∑FFDI are ambient drivers and/or preconditioning factors (i.e. drought), and certainly it is not clear whether the ∑FFDI is due to the frequency distributions of higher FFDI ratings or increases in the range of FFDI values.

Interestingly, all these studies are based on frequency assessment and probability distribution functions rather than on using *extreme* statistical assessment methods such as generalised *extreme* (GEV) or Pareto distributions (GPD) (Douglas, 2012).

Recent work by the Office of Environment and Heritage in NSW considered the application of the Weather Research and Forecasting model (WRF) which is an open source regional climate model (OEH, 2012).

An extract of observed versus projected outputs from the WRF model are given in Table 4.4 below at 50 km and 10 km grid resolution (for the period 1972-2009). This table shows that there is a bias to underestimating FFDI at the coast and an overestimation for inland areas when using the WRF. The report notes that these biases arise from humidity errors for average (and ∑FFDI) values, and wind speed errors at the *extremes*.

Table 4.4: Comparison between observed and predicted annual ∑FFDI and days exceeding FFDI 50 using the WRF (GCM) model (source OEH, 2012)

Station	**Annual cumulative FFDI**			**Days per year over FFDI 50**		
	Observed	WRF 50km	WRF 10km	Observed	WRF 50km	WRF 10km
Bourke	5735	7589	7048	6.8	13.9	13.6
Brisbane	1855	1976	1289	0.7	0.2	0.1
Broken Hill	4432	8115	7324	2.4	13.4	13.8
Canberra	2417	2513	2362	1.1	0.2	0.6
Casino	2305	1278	1970	1.9	0.0	0.7
Cobar	5035	6564	5725	5.4	7.2	7.0
Coffs Harbour	1167	1492	693	0.2	0.0	0.0
Dubbo	3577	4785	4038	2.7	1.9	2.4
Hay	3350	6258	5552	1.0	6.9	8.6
Lismore	1728	1278	1142	0.3	0.00	0.2
Mildura	5284	6821	6532	8.4	7.5	12.7
Moree	4198	5801	5020	3.2	3.6	3.7
Nowra	1762	1721	1442	1.0	0.1	0.2
Richmond	2469	2272	2462	1.7	0.2	1.1
Sydney	1897	2216	1293	1.4	0.0	0.1
Tibooburra	7339	9095	8506	18.0	18.4	17.7
Wagga	3461	4608	3578	4.9	2.9	2.9
Wilcannia	6408	8200	7559	11.6	15.2	16.2
Williamtown	1914	1619	1184	1.6	0.1	0.2

Although the OEH (2012) paper expresses confidence in the use of WRF for capturing the overall distribution of FFDI, it does not appear to play a role in assessing *extreme* FFDI for bushfire design purposes. As with the other investigations, the focus of the report is still on the probability distribution and frequency of values rather than recurrence or return periods.

A preliminary study (Louis, 2014a) of recurrence using BoM and Lucas (2010) data sought to provide a NSW gridded fire danger rating at various recurrence levels. Louis (2014) used both a GPD and GEV assessment (although the latter proved to be a Gumbel assessment) for FFDI and followed initial work by Douglas (2012). However, the study when used in association with regional climate models with a reanalysed dataset, gave significantly under-estimated FFDI values for the 1:50 recurrence. Notwithstanding the challenges for climatic modelling, this study provided a benchmark for comparison at the *extreme* using GPD and Gumbel assessments (not GEV).

4.4 Summary

Many studies have considered individual components of weather such as drought, *extreme* temperatures, wind and rainfall as well as the role of the ENSO and IOD on weather. Such approaches are useful for considering broader changes in fire risk; however, they do not provide a suitable basis for developing the concept of a ‘design bushfire’ for land use planning or building practice which are to be based on considering likely extremes.

While existing climate change studies indicate changes in modelled annual average cumulative FFDI (∑FFDI), it is not clear whether the preconditioning driver of drought, or the ambient drivers of wind, temperature and humidity are largely responsible for these projected changes.

Preliminary metrics have been developed for FFDI, which may also be applicable for FMC and KBDI. It is clear that the role of *extreme* value assessments forms a part of the suite of metrics in developing design bushfire conditions.

It is of considerable importance for land-use planning and construction practice to have suitable bushfire design conditions, which is contingent on suitable fire weather descriptors. It is also important to ascertain the likely effects not only of climate change, but the trends in fire weather also under the influence of global climatic events such as ENSO and IOD.

CHAPTER 5 - STUDY AREA, DATA AND METHODOLOGY

5.1 Study Area

The State of NSW covers a large geographic area (nearly 805,000 square km – including the ACT and Lord Howe Island or over 80 million hectares for NSW plus 260,000 hectares for the ACT) and there were 152 Councils plus Lord Howe Island in 2015 plus the Unincorporated area, of which some 120 are considered to have bushfire prone areas (NSW RFS, 2006). At the time of writing, the NSW Government was in the process of consolidating some Council areas, a process which is not complete.

In the present study, the development of a set of geographically specific bushfire scenarios for land use planning purposes and construction practice requires both a robust and practical dataset, as well as suitable methodologies for the development of 'design bushfire' conditions. For more general use, the methodologies should also be capable of execution by practitioners without the need for highly specialised software applications.

The relevant data requirements are related to the temporal and spatial distributions of weather parameters, the representative climatic conditions and the characteristics of the vegetation cover within the landscape. The State of NSW (and the ACT) has a diverse array of vegetation communities, topographical features and climatic patterns (Keith, 2004).As discussed previously in Chapter 2, topographical features are more local in nature and can be generalised for the purposes of the current study.

As identified in Chapter 4, the analysis of climatic considerations ideally requires data sets of 30 years duration or more and may involve the derivation of fire weather indicators (e.g. FFDI or fuel moisture) as inputs to bushfire behaviour models. In this study, data has been obtained (from BoM) for weather stations in NSW identified as appropriate within the regional context of fire weather districts (RFS, 2006). In some cases, data was derived from additional datasets assembled from complementary/supplementary sources. The selection of suitable weather stations to represent broader fire weather districts is not straight forward. Such selections may be limited by data availability and the representativeness of the geographical features within the broader landscape. To determine bushfire considerations for land-use planning and construction practice, vegetation distribution and fuel characteristics within the fire weather areas will also be required.

Chapter 3 provides the first comprehensive assessment of fuel characteristics(fuel load and fuel hazard scores) for NSW, although the basis for such has been developed in a series of 6 studies by the University of Wollongong (Watson, 2010). This vegetation data was spatially located in association with regional weather locations during the current study.

5.2 Regional Landscapes and Data Requirements

In Chapter 2, the forest fire behaviour models considered appropriate for the current study have been described, namely the FFDM5 and DEFFM models. The two key forest fire behaviour models being considered derive their fire behaviour conditions from different vegetation or fuel parameters, and from different fire weather parameters.

Table 5.1 provides a comparison of input data requirements in terms of fuel (vegetation) and weather for these two models.

Table 5.1: Input requirements for rates of spread and flame heights in FFDM5 and DEFFM models

Input	**FFDM5**	**DEFFM**
Fuel	Fuel load (tonnes per hectare) - Sub-canopy fuels - Canopy fuels	Fuel structure - Hazard scores (or ratings) - Fuel layers (heights)
Weather (climate)	FFDI - Drought (DF and/or KBDI) - Temperature (daily max) - Relative Humidity (3pm) - Wind speed (3pm)	Wind speed (3pm) Fuel moisture - Temperature (daily max) - Relative Humidity (3pm)

In this section, NSW is broken into 21 regional landscapes, firstly based on the climatic conditions (fire weather districts/areas) which prevail in those areas, and secondly the distribution of forest and woodland vegetation within those landscapes.

5.2.1 NSW fire weather districts

The measurement of weather and climatic data collection is undertaken routinely across the landscape. New South Wales is divided into 21 fire weather districts (or fire areas) by the Bureau of Meteorology (and NSW Rural Fire Service - *Rural Fire Regulations 2013*). In each of the districts, the Bureau of Meteorology has a series of automated weather stations collecting time series data for the normal range of parameters such as, temperature, rainfall, humidity and wind speed/direction.

The Bureau of Meteorology (BoM) also calculates ongoing values for Forest Fire Danger Index (FFDI) and Grassland Fire Danger Index (GFDI) based on these parameters. In some cases, FFDI has been determined by BoM retrospectively from limited data and for some stations key parameter data may be absent. In either case, there is not continuous data that extends 30 years for all the weather parameters to determine FFDI at all weather stations. The 21 fire weather districts adopted by the Bureau of Meteorology and NSW Rural Fire Service in New South Wales (ACT is included as part of NSW for this analysis) are illustrated in Figure 5.1.

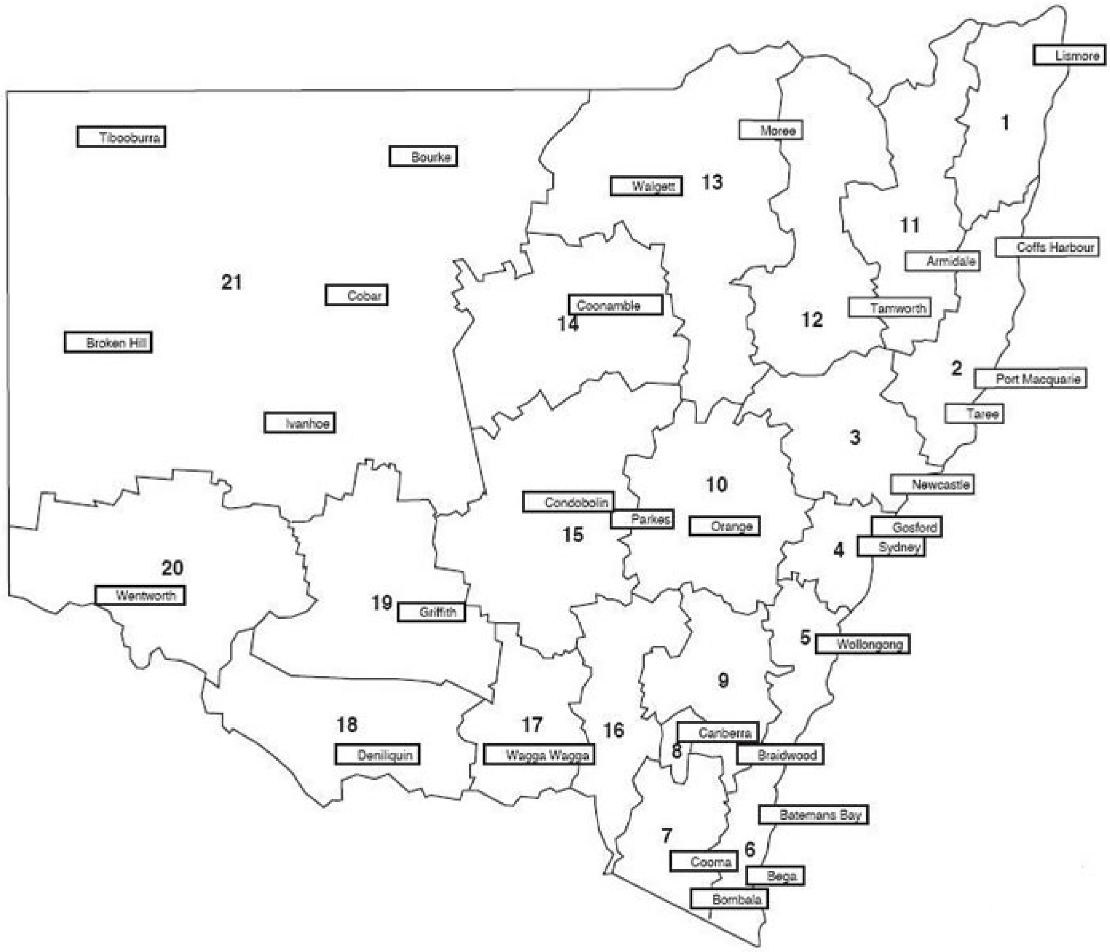


Figure 5.1: NSW Fire Weather Areas/Districts showing some major weather stations (Source: RFS, 2006)

Table 5.2 provides a summary of NSW RFS Fire Weather Areas, BoM weather forecast districts and local government areas.

Table 5.2: NSW RFS Fire Weather Districts, Bureau of Meteorology Forecast Districts and Local Government Areas

District Number	Fire Weather District by RFS	Forecast Area by BoM	Local Government Areas (as at 1 May 2016)
1.	FAR NORTH COAST	North Coast	Ballina, Byron, Clarence Valley, Kyogle, Lismore, Richmond Valley, Tweed
2.	NORTH COAST	Mid North Coast	Bellingen, Coffs Harbour, Gloucester, Great Lakes, Greater Taree, Hastings, Kempsey, Nambucca.
3.	GREATER HUNTER	Hunter	Cessnock, Dungog, Lake Macquarie, Maitland, Muswellbrook, Newcastle, Port Stephens, Singleton, Upper Hunter.
4.	GREATER SYDNEY REGION	Sydney (Metropolitan)	All Sydney Metropolitan Councils plus Gosford, Blue Mountains, Hawkesbury and Wyong.
5.	ILLAWARRA/ SHOALHAVEN	Illawarra	Kiama , Shellharbour, Shoalhaven, Wingecarribee, Wollondilly, Wollongong.
6.	FAR SOUTH COAST	South Coast	Bega Valley, Eurobodalla
7.	MONARO ALPINE		Bombala, Cooma Monaro, Snowy River.
8.	AUSTRALIAN CAPITAL TERRITORY	Australian Capital Territory	Australian Capital Territory.
9.	SOUTHERN RANGES	Southern Tablelands	Palerang, Goulburn-Mulwaree, Queanbeyan, Upper Lachlan, Yass Valley.
10.	CENTRAL RANGES	Central Tablelands	Bathurst , Blayney, Cabonne, Cowra, Lithgow, Mid Western Regional, Oberon, Orange.
11.	NEW ENGLAND	Northern Tablelands	Armidale Dumaresq, Glen Innes Severn, Guyra, Tenterfield, Uralla, Walcha.
12.	NORTHERN SLOPES	North Western Slopes and Plains	Gunnedah, Gwydir, Inverell, Liverpool Plains, Tamworth Regional.
13.	NORTH WESTERN	North Western Slopes and Plains	Moree Plains, Narrabri, Walgett, Warrumbungle.
14.	UPPER CENTRAL WEST PLAINS	Central West Slopes and Plains	Bogan, Coonamble, Gilgandra, Warren
15	LOWER CENTRAL WEST PLAINS	Central West Slopes and Plains	Dubbo, Forbes, Lachlan, Narromine, Parkes, Temora, Weddin, Wellington, Bland.
16	SOUTHERN SLOPES	South West Slopes	Boorowa, Cootamundra, Gundagai, Harden, Tumbarumba, Tumut, Young.
17.	EASTERN RIVERINA	South West Slopes	Albury, Coolamon, Greater Hume, Junee, Lockhart, Wagga Wagga
18.	SOUTHERN RIVERINA	Riverina	Berrigan, Conargo, Corowa, Deniliquin, Jerilderie, Murray, Urana, Wakool.
19.	NORTHERN RIVERINA	Riverina	Carrathool, Griffith, Hay, Leeton, Murrumbidgee, Narrandera.
20.	SOUTH WESTERN	Lower Western	Balranald, Wentworth
21.	FAR WESTERN	Upper Western	Bourke, Brewarrina, Broken Hill, Central Darling, Cobar, Unincorporated NSW.

Each fire weather district is comprised of a number of local council areas. It should be noted that these administrative forecast areas have been used for determining total fire bans and daily predicted fire weather conditions and as such, have continued to be used for the present study. In general, the RFS descriptor of fire weather district or the BoM weather station name will be used in the current study.

As such the geographic area of the fire weather districts are based on administrative boundaries rather than broader bio-geographical aspects of the landscape (i.e. soils, topography and vegetation type and cover) (Thackway and Creswell, 1995).

5.2.2 NSW weather stations and data availability

In 2009, there were 112 weather stations in NSW with records for the period from 1950-2010(BoM website, 2009). Some of these are either no longer operating or have been relocated to nearby positions. The data captured by these stations varies significantly, with most capturing daily rainfall, temperature (0900 and 1500 hrs), and wind speed/direction. However, early data records are often incomplete and rarely contained relative humidity.

An important consideration for the current study is to select a representative weather station within each of the 21 fire weather areas which have:

- significant years of data (i.e. 30 years or greater if possible); and
- representativeness of the broader geographical conditions in terms of climate, vegetation (notably forests or woodlands) and topography.

For example, some weather stations may be located close to the coast and influenced by on-shore breezes which can provide a false sense of climatic conditions across the fire weather areas concerned. Another point worth noting is that the fire weather districts located further west tend to be larger in size than coastal areas, and hence stations will be located remotely from other parts of the districts, potentially reducing their representativeness of climatic conditions. Conversely, larger western areas share similar topographical conditions, with less variation in terms of elevation and/or large water bodies.

The most notable of these variations are to be found in the Greater Sydney and Cooma-Monaro fire weather districts. The Greater Sydney district has stronger coastal influences than the western Sydney plains and the elevated Blue Mountains areas. In the Cooma-

Monaro Fire Weather District, the Australian Alps are significantly higher than the surrounding Monaro plains areas to the north and east and as such, alpine areas should display moderated fire weather conditions.

The following three different datasets were available from the Bureau of Meteorology for the current study:

- the National Fire Weather Dataset (FFDI and input parameters based on 1500 hr) for the period 1972 to 2010 for 77 stations nationwide. Of these, there are18 NSW weather stations within the National Fire Weather Dataset that could be used for the present study in NSW), although not all datasets go back as far as 1972 (Lucas, 2010);

- the NSW Ground Moisture Dataset for 88 weather stations which provides drought indices (DF, KBDI) and maximum daily temperature and rainfall data and generally covers the period 1994-2010; and

- the NSW 1500 hr weather dataset for 112 NSW weather stations covering 15:00hr (AEST) wind speed/direction, humidity, temperature and daily rainfall back to 1950 where available.

The selection process used to determine suitable weather station data is as follows:

- locate all weather stations provided under the National Historical Fire Weather dataset (Lucas, 2010) within a fire weather district, and choose those stations with the longest and most complete record;

- where a fire weather area has no national data, consider all State Historical Fire Weather datasets available from the BoM and choose the stations with the most complete record and capable of calculating FFDI and fuel moisture;

- where more than one comprehensive record can be located, choose a station which has the best combination of centrality to the fire weather area, is located closest to the greatest development or development potential for housing and population growth;

- consolidate incomplete data with other station data from either the same general locality (i.e. township) or with characteristics similar to and within the same fire weather district; and
- preference is given to national data over state data unless the quality of the record is not considered adequately comprehensive.

Appendix 1 provides an overview of the weather stations and site characteristics chosen for each fire weather district within the current study including the location (latitude/longitude), elevation, period of data and gaps, in some cases, alternate datasets which have not been selected are also indicated.

For the present study, 22 preliminary weather stations were chosen with at least one representative station for each fire weather district. The only exception was for Greater Sydney (District 4) where two stations were initially considered, one being on the coast (Sydney Airport) and one farther inland in western Sydney (Richmond). Unfortunately, due to a significant absence of earlier data, Richmond has not been used directly. A comparison based on the limited data for Richmond was considered so as to assess whether conditions would be different from the coastal location at Sydney Airport.

The station of Mildura is located in Victorian close to the NSW border near Wentworth in the south western fire weather area (District 20). The Jervis Bay Territory, though part of the Australian Capital Territory jurisdiction, is grouped with the Illawarra/Shoalhaven area (District 5) because of its geographic location. Lord Howe Island has not been considered due to its isolation and unique vegetation characteristics (mostly remnant rainforest). The ACT (District 8) has been included as it has its own data and is located within and surrounded by the greater NSW landscape.

One weather station (Armidale, District 11) is located at a relatively high elevation, and initially this was thought to possibly not be representative of the fire weather district. The district is highly variable due to the dissected nature of the landscape, with high plains, and deep gorges. An analysis of the nearby townships in the fire weather district indicates that each of the populated areas share similar altitudes. This is shown in Table 5.3. Inverell (580m) which is on the edge of the district could be considered part of the neighbouring district (North-Western).

Table 5.3: New England Townships and Elevations

Township	Elevation (m)	Township	Elevation (m)
Armidale	1079	Glenn Innes	1062
Guyra	1275	Walcha	1050
Tenterfield	1100	Uralla	1012

Data used in the present study is drawn from the National Fire Weather Dataset (13 stations) and from the NSW Ground Moisture dataset (10 stations) in combination with the BoM 15:00 hr dataset. Two (2) weather stations, Richmond (Greater Sydney) and Casino (Far North Coast), were only subject to preliminary investigation, with Sydney and Grafton being used more broadly in Chapters 6, 7 and 8.

5.2.3 Forest and grassy woodland distribution in NSW

The distribution of forest and woodlands in NSW is largely found along the coastal areas and inland as far as the ranges and slopes of western NSW. The characteristics and general distribution of wet sclerophyll, dry sclerophyll forests and grassy woodlands have been described in Chapter 3.

Keith and Simpson (2010) identified that at that time, it had not been feasible to either assess the accuracy of mapping from the source maps, and that available data did not provide a comprehensive coverage of vegetation formations throughout NSW.

The NSW vegetation data were obtained under licence from the Office of Heritage through the NSW Rural Fire Service. The data is the complete available vegetation classes described by Keith and Simpson (2010).

Although there are still further refinements which could be achieved for improved accuracy, the spatial extent of vegetation formations and classes have been estimated from the OEH data for the purposes of the current study. Vegetation data has, for the current study, been generally mapped at the level of formation (and sub-formation) and most vegetation classes according to the Keith (2004) classification using Arc ® GIS software located within the 21fire weather districts. Appendix 2 provides a summary of the data resolution characteristics and extent for vegetation mapping by fire weather districts (Keith and Simpson, 2010).The size of each vegetation formation (and sub-formation) were also calculated across NSW and within each fire weather district.

The proportion of each vegetation class was then mapped as part of the current study and its proportion within that fire weather area. The proportion of different vegetation formations as represented in NSW is summarised in Table 5.4.

In addition, fuel characteristics will also need to be assessed for each class within the dry sclerophyll, wet sclerophyll and grassy woodland formations as identified by Keith and Simpson (2010). These formations conform with the bushfire behaviour models sed in the current study and described in Chapter 2. The extent of forest and grassy woodland vegetation formations within NSW Fire Weather Districts are described further in section 5.2.4.

Table 5.4: NSW Vegetation formations area and proportion of NSW landscape(Source: OEH vegetation data, after Keith and Simpson, 2010)

Vegetation Formation (Keith, 2004)	Hectares	Proportion (%)
Alpine complex	151453	0.19
Arid shrublands (Acacia sub-formation)	8841743	11.04
Arid shrublands (Chenopod sub-formation)	6967191	8.70
Cleared	30690855	38.33
Dry sclerophyll forests (Shrub/grass sub-formation)	2763948	3.45
Dry sclerophyll forests (Shrubby sub-formation)	4830906	6.03
Forested wetlands	1028282	1.28
Freshwater wetlands	1326811	1.66
Grasslands	1336966	1.67
Grassy woodlands	1841057	2.30
Heathlands	172036	0.21
Not mapped	51443	0.06
Rainforests	549672	0.69
Saline wetlands	61355	0.08
Semi-arid woodlands (Grassy sub-formation)	4753257	5.94
Semi-arid woodlands (Shrubby sub-formation)	11601552	14.49
Wet sclerophyll forests (Grassy sub-formation)	1739473	2.17
Wet sclerophyll forests (Shrubby sub-formation)	1353782	1.69
Total	79910327	99.98[#]

Far right column does not equal 100% due to rounding of fractions to two decimal places.

Additional classes within the rainforest, scrub/shrubland (heath) formation, arid shrublands and semi-arid woodlands have also been mapped. Areas of western NSW without any specific identified class have been classed as grasslands. The areas of urban or township areas have been mapped separately. Figure 5.3 shows the broad spatial distribution of forest and grassy woodland formations within the current study.

5.2.4 Extent of vegetation classes within fire weather districts

For the current study, vegetation was mapped across NSW and the extent of each of the forest formations and classes (i.e. WSF, DSF and GW) determined by fire weather districts. Appendix 3 provides a detailed tabulated summary of each of the forest and grassy woodland vegetation (sub) formations and classes found within each of the 21 NSW fire weather districts.

Keith (2004) in mapping of vegetation formations does not specifically identify either WSF or DSF within the Western part of NSW (i.e. District 19-21). However, the mapping process undertaken during the current study was closely scrutinised using Arc® GIS to ascertain whether there was a sizeable amount of forest vegetation that could be identified within those districts.

Of the 21 fire weather districts, one (20. South-western) has no current recorded extant of forest vegetation classes. The Far Western area (21), which is the largest of the fire weather areas, has some scattered (approx. 7, 300 Ha) of grassy woodlands present and only 390 Ha of DSF vegetation. The Northern Riverina area (19) has approximately 149 Ha of the shrub/grass sub-formation of DSF, with some 18,000 Ha of the scattered grassy sub-formation DSF, and as with both districts 20 and 21, are widely dispersed over a large region and considered to be effectively absent due to past clearing and grazing. The predominant forest vegetation formation is the grassy woodlands which forms also only some 28,000 Ha in this large landscape. Therefore, each of these three fire weather areas has **not** been considered further in assessing forest fire behaviour outcomes. Together, these three areas form nearly one-third of the NSW land area and forms the western part of NSW.

The Southern Riverina (18) district has only a limited extent of grassy woodlands (almost 54,000 Ha), which is found at the eastern extremity of the area, with no DSF or WSF present. All other fire weather areas, have considerably greater than 50,000 Ha in forest vegetation classes within their boundaries, although seven (12 Northern Slopes, 13 North-western, 14 Upper Central Western Plains, 15 Lower Central Western Plains, 16 Southern Slopes, 17 Eastern Riverina, and 18 Southern Riverina) have negligible, if any, presence of

WSFs within their boundaries. These are dominated by grassy woodlands, but with a significant presence of DSFs (other than the Eastern Riverina).

As such, 18 fire weather districts will be assessed in terms of comparable fire weather and vegetation conditions, although five of these will only have DSF and grassy woodlands assessed, and only one with grassy woodlands being assessed. The ACT fire weather area (8) has no recorded DSF grassy/shrubby sub-formation.

Table 5.5 provides a summary overview of the effective presence/absence of each of the 5 (sub-) formations found within each of the 18 weather districts to be assessed.

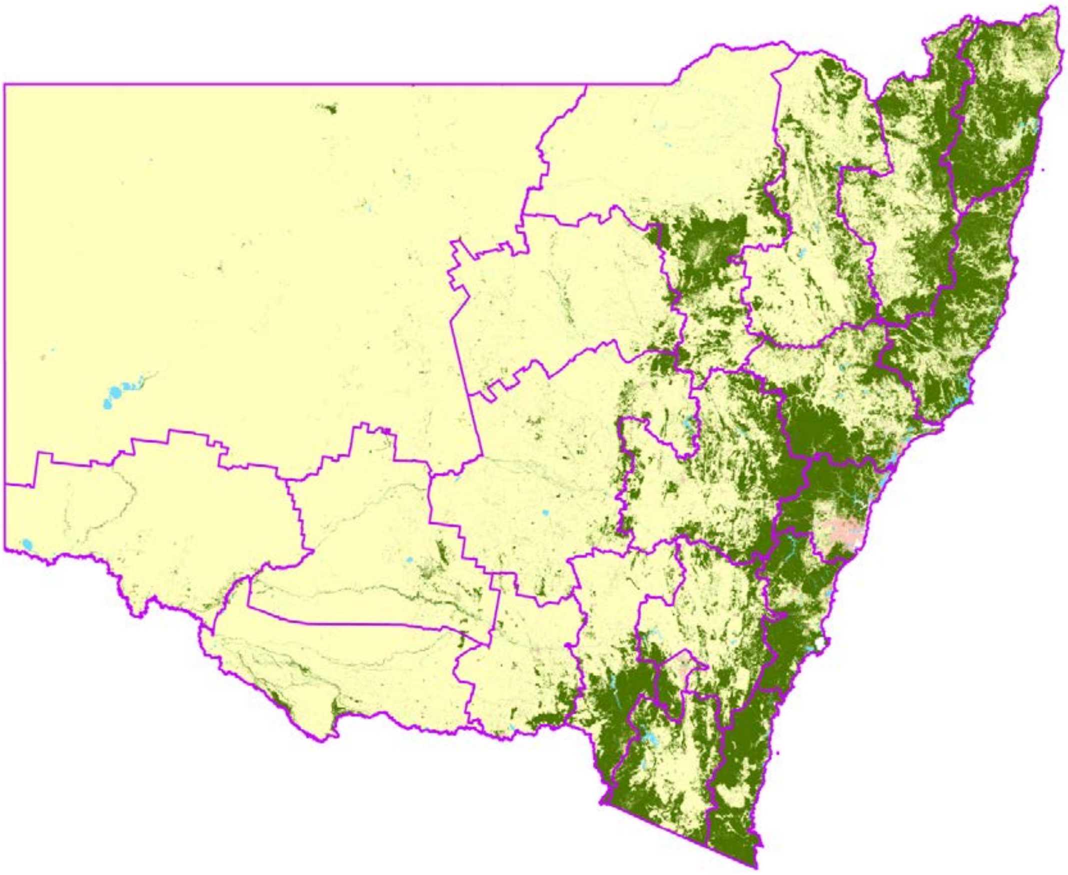
Table 5.5: Summary of presence of Forest vegetation sub-formations and Grassy Woodland formation within NSW fire weather areas

Forest Group	NSW Fire Weather District (Forecast Areas) Numbers																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
DSFs	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
DSFg	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	
WSFs	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓							
WSFg	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓							
GW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

DSFs =dry sclerophyll forest (shrubby sub-formation),
DSFg = dry sclerophyll (grassy/shrub sub-formation),
WSFg = wet sclerophyll forest (grassy sub-formation),
WSFs = wet sclerophyll forests (shrubby sub-formations),
GW = grassy woodlands.

In Chapter 3, the general extent of vegetation formations, and notably forest and grassy woodland formations indicated that wet sclerophyll forests are largely constrained to the coast and tablelands, with grassy woodlands being predominant within the slopes and plains. It can be seen from both the descriptions in Chapters 3 and confirmed in Table 5.4 above, that the dry sclerophyll forests are more broadly distributed within the central and eastern divisions of NSW.

Figure 5.2 shows the mapped distribution of the forests and grassy woodlands of NSW but does not include the arid shrublands of far western NSW, which fall outside the forest models used for the present study. The grasslands and semi-arid woodlands of central and western NSW have also been grouped for convenience, as these do not fall within the forest fire behaviour models being considered.



forests (including rainforest); grassy woodlands; cleared (urban);

grasslands and semi-arid woodlands; weather district boundaries.

Figure 5.2: Distribution of forests and grassy woodlands over weather districts of NSW (Source: RFS, after Keith and Simpson, 2010)

5.3 Climate Data Collection

This section of the study describes the three different datasets used to derive district fire (fire weather areas) weather conditions. In section 5.2.2 above, it was identified that three datasets were available from the Bureau of Meteorology considered suitable for the present investigation. These are the:

a) the National Historical Fire Weather Database (1972-2015) described by Lucas (2010);

b) the Ground Moisture dataset for 88 weather stations (1994-2015); and

c) the 3:00pm Daily dataset for all 112 weather stations in the State over the period 1950-2015.

A description of the data and their availability for use in the current study is provided below.

5.3.1 National Historical Fire Weather Dataset (1972-2015)

The Bureau of Meteorology data acquired under the National Historical Fire Weather Dataset program which was described and developed by Lucas (2010) covers 77 stations nationwide, initially for the period beginning 1974 to the end of 2009. This dataset contains the following daily data:

- Derived FFDI
- Derived GFDI
- Maximum temperature (^{o}C)
- 3pm relative humidity (%)
- 3pm wind speed (kph) and wind direction
- Drought factor
- KBDI (mm)
- Rainfall (mm).

The initial dataset of 37.5 years was extended to 43.5 years late in the study with access to data to the end of 2015 (available in 2016). There are significant limitations with this dataset (Lucas, 2010),although it is generally comprehensive with most of the data now covering a period of 43.5 years. In particular, the FFDI evaluation was based on 3:00 pm (local time) data measurement of wind speed and relative humidity. However, the 3:00 pm data for wind speed and relative humidity does not necessary represent the worst case scenario for the day. For example, the lowest relative humidity during a day could be lower than that recorded at 3:00 pm and would be associated with maximum temperature (see Figure 4.4). The time of 3:00pm was standardised and arose because earlier weather stations, prior to being automated, only collected 9:00 am and 3:00 pm (and some 12:00 md and 6:00 pm) data for some parameters. Notwithstanding such limitations, the derivation of FFDI as a non-dimensional parameter is not meant to be an exact calculation, having regard to the confidence limits associated with such models. Although overall, the calculated FFDI is anticipated to be less than the daily maximum, the dataset has been used in other studies (Clarke et al, 2011, Clarke et al, 2012, Lucas et al, 2007, and Hennessey et al, 2005). The dataset can also be used to calculate daily forest fuel moisture (Cruz, 2015).

In a number of cases there are significant gaps in data for a weather station. For example, there may be missing data for 3:00pm relative humidity, daily maximum temperature or 3:00 pm wind speed on particular days. Throughout the current study, gaps for such missing data were filled through either test data or ‘borrowed’ data from nearby stations. Test data was used where no other suitable data of comparable quality couldbe found. Test data uses data of previous or successive days or maintains a trend within the existing data. For example, in winter, temperatures are lower and humidity is higher and the pattern within the data set can be maintained with FFDIs not likely to be high. In summer, test data may be generally the same but greater care is required due to the significance that may be derived from use of such data. Weather stations which had a relatively complete record were selected over those stations where data was relatively poor or gaps were significant. DF, Tmax and KBDI were consistently of high quality and did not need gap filling. Wind speed/direction and relative humidity gaps, were the most common reason for missing data. Information on data quality for weather stations is provided in Appendix 1.

The calculation of FMC (Cruz, et al 2015a) can be biased as a low value in the absence of a realistic RH value. As the most common reason for missing data is related to RH in the early dataset, without some gap filling, this could have a significant bias in the early years to artificially lower RH, with higher relative RH in later years.

Borrowed data occurred where gaps could be filled by geographically close locations. Grafton for example had three overlapping datasets, due to site relocations and or upgrades to AWS standards.

Due to the uneven distribution of weather stations, there is a geographical bias to far western districts which have relatively large spatial areas. As a result, of the 18 weather stations available, only 12 of the 21 fire weather areas were covered and had weather stations to represent district (fire weather area) conditions. In some cases stations were used in adjoining States/Territories, such as Mildura on the Victorian/NSW border and the ACT. The remaining fire weather districts which were not covered by this dataset require additional dataset from another source. This is discussed in section 5.3.2 below.

An example of the format for National Historical Fire Weather Dataset is shown in Table 5.6.

Table 5.6: Example of National Historical Fire Weather Dataset (Lucas, 2010)

mm	dd	yyyy	FFDI	GFDI	T_{max}	RH_{3pm}	Us	Direction	DF	KBDI	Rain
6	1	1972	0	2	18.2	76	14.8	SW	0.2	0	7.4
6	2	1972	0	1	19.6	84	5.4	SW	0.9	0.4	1.8
6	3	1972	0	2	19.9	73	13	SSE	1.7	0	2.8
6	4	1972	0	2	19.7	66	11.2	S	1.2	0	9.1
6	5	1972	0	18	19.7	79	44.6	SSW	1.8	2.2	0
6	6	1972	2	15	19.4	66	38.9	S	3.9	4.3	4.3

5.3.2 Bureau of Meteorology NSW Ground Moisture data (1994-2015)

In addition to the National Historical Fire Weather Dataset, NSW specific data on drought indices was acquired from BoM and was referred to as the NSW Ground Moisture components dataset. This historical data is for 88 NSW locations (which may or may not correspond to the stations in the national dataset) and comprises principally various drought indices (including KBDI and SDI), Drought Factor, maximum daily temperature and rainfall. The latter two parameters are up to 9:00 am and really represent inputs for the day prior. As such, on its own this data only provides Drought Factor and daily maximum temperatures for deriving FFDI and temperature for fuel moisture calculations. The Ground Moisture dataset does not include 3:00 pm relative humidity or wind speed/direction.

The Ground Moisture data covers the period from 1994 to early 2016. As such, the data only just cover the 20 year dataset needed for EVA climatic considerations (see 5.5.1

below) described by Lindsey (2003). In some cases data does not cover the whole period. Table 5.7 provides an example of the Ground Moisture dataset used for NSW.

Table 5.7: Example of data used from NSW Ground Moisture Dataset

Date	KBDI	SDI Primary	SDI Secondary	DF Forest	Rain	Air Temp
15/03/2016	69	146	113	8.6	3.4	28
14/03/2016	68	146	113	8.6	0	29

Of the original 88 stations available from the NSW Ground Moisture component dataset provided21 weather stations for the 8 remaining fire weather districts not already covered in the National dataset. Of those 21 stations, 10 stations were chosen because of their geographical spread within these fire weather districts and the extent of available historical data. The characteristics and extent of historical data for these weather stations are also described in Appendix 1.

5.3.3 Bureau of Meteorology Daily 1500 hrs weather data (1950-2015)

To complement the missing information in the NSW Ground Moisture dataset, additional data from the Bureau of Meteorology's 1500 (3:00 pm AEST) daily weather dataset was obtained for 112 NSW weather stations. The data are of various ages and goes back as far as 1950. In a number of cases, weather stations have slightly changed locations and with the introduction of Automated Weather Stations (AWS) there has been an expansion of the number of weather parameters recorded and ongoing monitoring throughout the day. However, records for all stations are of varying quality. The major challenge is to match up the records of wind speed and humidity with the Ground Moisture records described in the foregoing subsection 5.3.2. The importance of these records for the current study is not in directly determining FFDI (although with rainfall and temperature this could be done) but in supplying relative humidity and wind speed data for the derivation of FFDI and with maximum daily temperature to determine fuel moisture.

Again, in some cases gaps may be present and were filled as described in 5.3.1 above. In some cases, gap filling was easier with more alternate and overlapping localised weather stations available for comparison purposes.

The Far South Coast fire weather district, for example, had significant gaps in all the weather station locations. Due to its slightly better dataset in the same fire weather district, the Batemans Bay station was chosen to represent this fire weather district. Gap filling was undertaken having regard to the prior and post daily patterns of existing data. This means that filled data would under-estimate the likely weather conditions.

5.3.4 SOI data

In addition to the above data sets for deriving FFDI and fuel moisture, Chapter 4 identified that any trends in global conditions, outside of climate change, would also be considered. The Southern Oscillation Index (SOI) data is publicly available from the Bureau of Meteorology's website in text format which is readily converted to Excel format. Within the period of the current study, the influence of SOI under ENSO (i.e. drier and hotter) conditions was strongest in the years 1982-83, 1997-99 and 2006-07 (Lucas et al, 2007). The dataset is a monthly index and covers the years 1972-2009, corresponding to the period of data initially available for the National Dataset and NSW 1500 hrs dataset.

In Chapter 4, it was found that the SOI values indicated that on a monthly basis, the overall trend was towards wetter conditions. However, the data are widely fluctuating. To address this challenge, monthly SOI data is grouped (summed) in the current study by bushfire season, averaging out large fluctuations.

5.4 Methodology for Deriving FFDI and Fuel Moisture

The National Historical Fire Weather Dataset includes daily FFDI based on daily DF, maximum daily temperature, 3:00 pm relative humidity and 3:00 pm wind speed (and direction). It also includes KBDI (see 5.3 above).

NSW Ground Moisture (which includes KBDI, DF and Tmax) dataset was combined with the NSW daily 3:00pm dataset (with relative humidity and wind speed) to provide a new dataset consistent with the National Dataset and capable of determining FFDI using Eq. 2.2.For simplicity, this new combined and derived FFDI dataset will be referred to as the NSW Historical Fire Weather Dataset so as to differentiate it from that developed by Lucas (2010).

5.4.1 Preliminary data processing to derive FFDI

While the National Historical Fire Weather Dataset generally provides FFDI for 18 NSW stations for the period 1972-2009, there are some exceptions, both in period of coverage and gaps within the data period(see Appendix 1). These gaps were filled by using two complementary datasets as described in subsections 5.3.1 and 5.3.3. The missing FFDI was derived from the recorded weather parameters using Eq. (2.2).

For the NSW Fire Weather component dataset, new spreadsheets were developed by combining the data from the 88 stations with comparable date data from the daily 3:00 pm historical record, matching daily 3:00 pm wind speed and direction, daily 3:00 pm relative humidity, daily 3:00 pm temperatures with daily KBDI, Drought Factors and maximum daily temperatures (which are offset by 1 day being maximums up to 9:00am from previous day). As described in Chapter 2 and Eq. (2.2), the drought factor evaluation depends on the number of days from values for the previous rainfall, the Drought Factor values in the beginning period of the record were absent due to the lack of information on the previous rainfall (Griffiths, 1999). These dates were supplied with data from nearby stations in the National Historical Fire Database. All daily FFDIs were then determined for all selected weather stations.

5.4.2 Deriving fuel moisture

Having compiled all data into a single format with calculated FFDIs, it was then necessary to calculate fuel moisture (Matthews, 2010). Fuel moisture content (FMC) was derived using the equations of Cruz et al (2015a) as described in Chapter 2 [Eq. (2.23)] and the daily data available for all 18 selected sites. This was necessary for both the 8 selected National Historical Fire Weather and the additional 10 stations from the NSW Historical Fire Weather dataset.

5.5 Methodology for Determining Design Bushfire

Past practice has been to consider the limited data available for a region and determine whether any of the following should be used in developing policy for land-use decision-making or construction:

a) FFDI has been exceeded on more than one recorded occasion;

b) FFDI which is a frequency percentile value of the dataset (e.g. 95% value of FFDI>12); or

c) derived FFDI from maximum values of wind speed, (lowest) relative humidity, maximum temperature and drought factor for summer data (see Chapter 1).

Each of these methods has significant shortfalls and do not represent a suitable approach to the assessment of fire weather, but have been used in the absence of a clear methodological and statistically appropriate approach (e.g. Douglas and Tan, 2005).

The development of a 'design bushfire' for land-use planning and construction practice purposes requires consideration of an appropriate set of climatic conditions and vegetation characteristics at the regional and sub-regional levels. For the current study, topographical features are assumed to be relevant at the site specific level.

For the FFDM5, the determination of *extreme* value FFDI values will be required using statistical approaches described below. Hasson (2008) has identified that using an *extreme* value technique would be preferred in the development of design FFDI but did not utilise such an approach. Fuel loads are described in terms of average fuel load (tonnes per hectare) for sub-canopy and total fuels (including canopy). These are described in Chapter 3.

For the DEFFM model, wind speeds will need to be derived from the FFDI data being winds at the *extreme* end under fire weather conditions. Fuel hazard score, height of elevated fuel and fuel moisture is also required. For fuel hazard score and height of elevated fuels, average values will also be used. For fuel moisture, values will need to correspond to *extreme* value assessment.

However, the most appropriate outcomes for the design bushfire considerations using the two fire behaviour models (i.e. FFDM5 and DEFFM) is to apply *extreme* value assessments to the outputs of rates of spread and flame heights (Douglas et al, 2016). Detailed discussions of the extreme value assessment methods are given in subsequent sections.

5.5.1 Frequency and percentile analysis of FFDI

Frequency and percentile analysis can be utilised where the variability of FFDI is examined over decadal timeframes. Frequency analysis, especially at the 95^{th} percentile of observations, gives a better understanding of the range of variability, and at the seasonal level, can assist in interpreting shifts in seasonal fire weather associated with climate change (Lucas, et al, 2007). Median (50^{th} percentile) values can show the severity of the fire season and over time shifts in fire season conditions. The study by Lucas et al (2007), also considered the number of days with FFDI≥25 as a measure of the 'normal' fire season. This is discussed in Section 5.6 below. This study suggests that at FFDIs of less than 25, there would be little error or bias arising from gap filling. The need to provide gap filling of data, means that some days (although small in number) could bias individual years. This can be resolved by smoothing out the noise (peaks and troughs) by using moving averages (Gorry, 1990) of adjoining periods. This is particularly important where trended analysis is being used to consider likely climate change (Chen et al, 2004; Katz et al, 2005). Similar approaches have been used by Crompton et al (2010) for SOI and IOD.

Douglas and Tan (2005) suggested that a 95 percentile of all recorded FFDI values of 12 or greater could be used in the absence of a comprehensive dataset of a weather station. FFDI's greater than 12, were considered the conditions under which it would become difficult to manage a prescribed fire (or hazard reduction burn) and which could escape and result in a wildfire (RFS, 2002). A minimum of 30 years of continuous data appears necessary (Lindsey, 2003).

From the above discussion, such a metric (i.e. 95% of FFDI≥12) can be undertaken for comparative purposes with EVA techniques and to determine its suitability as a policy setting for extreme fire weather conditions.

5.5.2 Extreme value analysis (EVA)

Extreme fire weather events are by their nature uncommon, and as such, the *extreme* value assessments can be used when considering planning for *extreme* weather events (Holmes and Moriarty, 1999). *Extreme* value assessment (EVA) allows, through regression analysis, the prediction of certain conditions for planning and construction practice purposes. *Extreme* value assessments are used in determining flood outcomes, temperatures (Dury, 1972), storms (Holmes and Moriarty, 1999) and other natural phenomena. However, little work has been done in relation to fire weather or fire behaviour in Australia or elsewhere (Douglas et al, 2014).

Previous climatic assessments have largely focussed on historical weather records and linear regression models (e.g. Andrews et al, 2003; Bradstock et al, 1998) but not Pareto distributions or other *extreme* value assessments. In the study of climate change projections for temperature by Hennessey et al (2011), decile scaling methods were preferred over GEV and were applied to various climatic models due to its relative simplicity. When applying GEV to global or regional climatic models, the GEV simulated events may be unrealistic and care should be exercised due to the challenges associated with the combination of weather conditions over which GCM can be applied to FFDI.

When using GCM for mapping projected rainfall *extremes* and climate change, Rafter and Abbs (2009) concluded that some models seem to give unrealistic increases in rainfall to most regions whereas another model (NCAR CCSM3.0) simulated more decreases than increases. This study reflected that simulations for *extremes* were less reliable than for averages.

Recent work by Cechet et al (2014), Louis (2014) and Sanabria et al (2014) have illustrated the role of *extreme* value assessments based on GPD to map fire weather (FFDI) return periods across the Australian landscape using GCM climatic models (e.g. CCAM Mark 2 and 3) and based on point data-sets. Such models can also consider the potential effects of climate change (Hennessey et al, 2005). Such mapping exercises are initially attractive but rely on complex models to translate a weather and climatic scenario for events which are occurring in different time frames and conditions (Perkins and Pitman, 2009). Also, Sanabria (2014) and Louis (2014) critically used different inputs for wind speed, which may give rise to slightly different results. Li and Heap (2011) has identified the challenges of environmental mapping under such conditions, which include the needs for larger numbers of data-points (i.e. weather stations) within a landscape for model enhancement. The rationale for care expressed by Hennessey et al (2011) in relation to a single weather parameter can be compounded by FFDI which relies on four input parameters to be modelled. Louis (2014) sought to compare GPD with seasonally adjusted Amax assessments for sites including the Lucas (2010) and Bureau of Meteorology data. This data can be used for the current study as identified in section 5.3.1. These results can be considered in the light of the current study, although little consideration was reported of likely correlation or goodness of fit.

Douglas et al (2014) presented a general *extreme* value approach to modeling of the recurrence of FFDI. This approach sets the selection of design bushfire on a more rigorous basis than the method used in the existing standard (AS 3959, 2009). Application of the method to limited weather districts in NSW has shown good correlations between the regression lines and the FFDI data.

The concept of annual occurrence of exceedance (or recurrence) for FFDI is used by the New South Wales (NSW) Rural Fire Service as a major input for determining the design bushfire conditions where an alternate approach is proposed (NSW RFS, 2006). Such assessments were not considered as part of the development of the NSW planning guides or construction practice, due largely to poor data availability.

The sensitivity of FFDI used to estimate fire danger throughout Australia has been considered by Williams et al (2001) and linked to increased recurrence of fires as measured in terms of VERY HIGH and EXTREME events and may be linked to maximum daily temperature. Similar considerations apply in relation to FMC (Sullivan, 2004) and KBDI (Melton, 1989). There has not been any literature identified using EVA techniques used for FMC or KBDI, either in Australia or overseas.

The current study draws upon three *extreme* value assessment methods to determine appropriate annual return periods (intervals) or recurrence for land-use and construction purposes. These are the Generalised Extreme Value (GEV) technique (Coles, 2004; Douglas, 2012), Annual Maxima (Gumbel, 2004) and Pareto Distribution technique (Reiss and Thomas, 2007a).

Under the theoretical considerations of *extreme* value (GEV and Annual Maxima) there are generally three families of uni-modal distributions which are commonly referred to as:

Type I – Gumbel distribution;

Type II – Frechet distribution; and

Type III – Weibull distribution.

FFDI is a composite index of parameters which have effective limits, at both the low end (cannot be 0 or less) and the high end, hence FFDI is limited, and therefore of the three distributions, is best described by the Weibull distribution. The Gumbel distribution decays exponentially, whereas the Frechet decays polynomially (Coles, 2004). All three families can be combined into a single distribution simplifying statistical interpretation and is referred to as the GEV analysis (Kotz and Nadarajah, 2000). These distributions are effectively considered asymptotic with a maximum threshold.

Similar to GEV, the Generalised Pareto (GPD) distribution has three sub-models (Reiss and Thomas, 2007a) as well and are referred to as:

Type 1 - Exponential

Type 2 - Pareto

Type 3 – Beta.

These three sub-models can also be unified into a single Generalised Pareto distribution (GPD).

The mathematical expression for each of these distributions is described in Coles (2004). The most relevant distributions to the current study and their corresponding recurrence analyses techniques are presented in the following.

a) Generalised Extreme Value (GEV)

The Generalised Extreme Value probability density function (GEV) is expressed by the following equation(Coles 2004):

$$f(x) = \exp\left\{-\left[1 + \varepsilon\left(\frac{z-\mu}{\sigma}\right)\right]^{-\frac{1}{\varepsilon}}\right\} \tag{5.1}$$

where $-\infty < \mu < \infty, \sigma > 0,$ and $-\infty < \varepsilon < \infty$.

The approach of the GEV recurrence analysis method is to examine and identify the highest values of a given parameter over the site record in order against its position in *n* years. (Makkonen, 2006).

In this approach, the top or the highest n+1 data points of any given parameter y are taken from a period of n years. The data points are then ranked according to their values: $y_m \geq y_{m+1}$ (m=1, 2, …,n). The return period x is evaluated according to plotted position:

$$x_m = (n + 1)/m \tag{5.2}$$

where m=1, 2, …, n+1.

The obtained set of n+1 data pairs (y_m, x_m) (m=1, 2, 3, …,n+1)can be plotted on a log-linear graph. The resultant curve usually follows a log function of the form (Makkonen, 2006):

$$y = \alpha\log(x) + \beta \tag{5.3}$$

where α and β are constants and are determined by regression analysis. The resultant curve is then extrapolated in a time-series analysis for prediction of recurrence values of *y* outside the range of original data. The log is a natural log, based on log-linear plotting positions.

This form of the GEV is versatile where length of data period approaches 20 years or over and the fire season (such as summer) cross over the calendar year. This is because the sequence of maximal data plotted is not calendar dependent (as in Gumbel- see below).

b) Gumbel or Annual Max (A_{max})

Under the Gumbel approach, the annual maximum value for each year is determined and ranked as with Eqs 5.2 and 5.3 of the GEV approach above. However, the bushfire season(s) generally fall over the October-March period, , requiring an assessment commencing on 1 June to align with winter, rather than the universal calendar year. The challenge for the Gumbel approach is that data is captured on an annual maximum basis and not maximally over the whole dataset as in the GEV approach.

The techniques used for plotting the data are the same as Eq 5.3, relying on annual maxima, rather than *n*+1 maxima within the dataset for GEV assessment. The probability density function distribution governing the Gumbel distribution (annual maxima) is of the form:

$$f(x) = \frac{1}{\beta}\exp\left(-\frac{x-\mu}{\beta}\right)\exp\left[-\exp\left(-\frac{x-\mu}{\beta}\right)\right] \tag{5.4}$$

where β and μ are distribution parameters, and the domain for x is $(0, \infty)$.

As the study of Louis (2014) already has adjusted for seasonality, the current study will also consider the effect of calendar rather than seasonal maximum values. Seasonality should not be an important factor, however, as it is possible to have multiple days being the highest in a single season, a seasonal assessment may give different results to that of calendar years. The resultant Gumbel values for the calendar years are therefore compared to the seasonal results of Louis (2014) in Chapter 6.

c) Generalised Pareto Distribution (GPD)

Unlike other EVA approaches, GPD relies on determining the proportion of exceedance values above a threshold. This is often referred to as a "peaks over threshold" approach (POT) where the parameter values are ranked and the proportion of values exceeding threshold values are then plotted in a similar way to GEV.

The probability density function for the generalised Pareto distribution (GPD) takes the form (Coles, 2004):

$$f(x) = \frac{1}{\sigma}\left[1 + \frac{\xi}{\sigma}(x - \mu)\right]^{-\left(1+\frac{1}{\xi}\right)} \tag{5.5}$$

For $x \geq \mu$ when $\xi \geq 0$ and $\mu \leq x \leq (\mu - \sigma/\xi)$ when $\xi < 0$.

To calculate average return intervals *(ARI)* (recurrence)a partial duration series dataset (as opposed to annual maximum) is constructed using:

$$ARI = \frac{Total\ Number\ of\ Datapoints}{Number\ of\ Datapoints\ where\ parameter\ value > threshold} \tag{5.6}$$

ARI is used in this context to differentiate GPD from GEV approaches.

Using the statistical fits to observations, we can calculate the return intervals for a given period using the formula (Coles, 2004; Louis, 2014):

$$E = \beta + \beta_1 \ln(ARI) + \varepsilon \tag{5.7}$$

Where E is the parameter value sought for the recurrence period (ARI) in years.β has the same effect as in Eq. 5.3 (intercept), and β_1 can be considered the shape parameter (i.e. α in Eq. 5.3). Where the sample population size is large, ε approaches and considered to be zero.

As such, this resultant line can be considered under the simplified form given in Eq. (5.3) above. This is useful for comparative purposes and does not require any further sophisticated software packages than that used in assessing GEV or A_{max}. For the purposes of the current study, the value of FFDI for a given annual return interval is what is required.

The advantage of the GPD approach is that it is not reliant on seasonal or calendar considerations. The disadvantage however, is that any missing or gap filled data will have a greater influence on the output than in either GEV or A_{max} approaches, especially where gaps are large or the number of years are smaller. In many cases, GPD is often used as the method of choice by climate researchers and meteorologists (Louis, 2014;Sanabria, 2014), particularly as there are source programs for this task (e.g. in *R*), making assessment easier. Source programs are less common for GEV and Gumbel but are available for some programs such as Xtreme ® (Reiss And Thomas, 2007).

5.6 Methods used for Examining Climate Change and Other Climatic Phenomena

5.6.1 Changes in annual, seasonal and monthly FFDI, FMC and KBDI

Hennessey et al (2005) and Lucas et al (2007) demonstrated that the influence of climate change could be observed through subtle shifts in FFDI. This may also be so for FMC and KBDI. These changes may occur in terms of:

- Annual-average cumulative FFDI (denoted ∑FFDI),
- Seasonal-average ∑FFDI, and
- Monthly-average ∑FFDI.

In addition, Lucas et al (2007) considered changes in the number of days in which FFDI exceeded key threshold values (e.g. FFDI ≥25 or FFDI≥50) and percentile analysis of FFDI (10%, median and 90% values) as a measure of changes in the fire season (i.e. it's extension or severity). These studies have been reviewed in part in Chapter 4.

The studies by Hennessey et al (2005) generated future weather data from computer simulations which may have over or under-representations of climate change, although the overall trend is clear. Lucas et al (2007) used historical data for the period 1973-2007, and extended the work of Hennessey et al (2004) whereas the current study has been able to extend this historical dataset further for the period from mid-1972 to the end of 2009 (and in some cases to 2015).

The changes in FFDI predicted by Hennessey et al (2005) and Lucas et al (2007) using GCM (CCAM2) for the three metrics of ∑FFDI (Annual average), average no. of days/year FFDI≥25, and average number of days FFDI≥50. Where climate change can be expected to be exhibited is where the frequency (number) of FFDI days exceeding a given threshold increases and the cumulative value (i.e. ∑FFDI) of such days also increases. The results of the Lucas et al (2007) study are presented in Table 5.8.

Table 5.8: Summary of results of sites studied for potential impacts of climate change (Lucas et al, 2007)

Weather Station	Weather (FFDI) data for period 1973-2007 (Lucas et al 2007)					
	Annual Average ∑FFDI	Predicted % increase in 2020	Annual Average No. of days FFDI≥25	Predicted Annual Average in 2020	Annual Average No. of days FFDI≥50	Predicted Annual Average in 2020
Coffs Hbr	1255	1-6	1.5	1.6-1.8	0.2	0.2-0.3
Williamtown	1984	1-9	10.3	10.8-12.8	1.4	1.6-2.3
Sydney	1897	1-10	7.6	7.8-9.4	1.2	1.3-1.7
Nowra	1768	0-7	8.8	8.7-10.3	1.1	1.0-1.6
Canberra	2493	3-11	16.8	18.3-22.8	1.6	1.7-2.2
Dubbo	3153	4-11	23	25.6-30.0	1.7	2.0-3.1
Moree	3973	4-12	30.5	34.5-41.1	2.2	2.4-3.6
Wagga Wagga	3319	3-10	32.6	34.8-40.3	4.2	4.7-5.9

The data in Table 5.8 provides a baseline from which to consider the current study's results.

The relevant methods used for the current study are briefly described below.

5.6.2 Annual-average and seasonal cumulative FFDI, FMC and KBDI

Most climatic conditions measured and presented to the public are in terms of averages or percentile values. The challenge in considering climate change however is that changes in FFDI may be subtle and not be apparent in averages or percentile values. To address this, the metric of cumulative FFDI, which is the summation of the daily FFDI (or FMC or KBDI) over the season or year is used (i.e. ∑FFDI). The year is defined from 1 June to 31 May, commencing in winter. Data provided by BoM through the National Historical Fire Weather database (Lucas, 2009) commences on 1 June, 1972. The NSW Historical database normally commences on 1 January, and hence, the first 5 months of data are not used. This also allows for the ease in assessing FFDI and FMC and KBDI data by season.

5.6.3 Number of threshold FFDI (FMC and KBDI) days

Within the context of the current study, a threshold is a parameter value which is considered to be critical in terms of increased severity of a bushfire hazard. Threshold values can be applied to FFDI, FMC and KBDI, all of which have been used historically to indicate significant changes in fire behaviour and are discussed in Chapter 2.

This simple metric is derived from the number of days which are equal to or exceed a threshold parameter, such as FFDI, FMC or KBDI and is derived annually commencing 1 June of each year.

Key threshold values for FFDI are FFDI$\geq$25 and FFDI$\geq$50 adopted by Lucas et al (2007).

For FMC, the threshold value 7% (severe bushfire behaviour) or less is suitable (Luke and McArthur, 1978).

For KBDI, the threshold value of 150mm was used largely corresponding to the point where fire behaviour was also considered unmanageable (Melton, 1989).

Shifts in seasonal and annual threshold parameters may provide some insights into either changes in climate and/or the effects of SOI on these parameters.

5.6.4 Moving average

When time series data, such as weather, is subject to influences which arise from errors in instrumentation and measurement (such as automatic weather stations) or from short term changes in environmental conditions which may have a large impact on climate, the moving average method can be employed to remove undesirable noise and truncations from the data (Chen et al, 2004). It can also be important in non-static conditions to deduce trends. However, these trends may form new static conditions due to environmental shifts.

In addition, some errors may exist in relation to uncertainty around the use of gap filling of data, which can be adjusted with the use of moving averages. As described previously in section 5.3, gap filling relies on internal trends within the dataset, as well as nearby weather stations as a guide to infilling of missing data. Such infilling methods are not considered problematic with EVA approaches. However, when addressing trend assessments on cumulative data, the moving average method can assist in removing bias arising both from short term climatic shifts (e.g. ENSO) or gap filling of data (Gorry, 1990).

This method is therefore useful in providing annualised trend data by using multiple moving years to derive these trends, especially where short term effects of broader climate factors may affect a single year (e.g. IOD). Annualised trends in ΣFFDI ($\sum$FMC and

∑KBDI) will need to be averaged from a moving 4 year period (also addressing leap years). With this in mind, the annual and seasonal cumulative FFDI described by Lucas (2007) can be enhanced by use of the moving average method annualising the 4 year period results. This can also be done for ∑FMC and ∑KBDI.

The resultant plots of time-series data for ∑FFDI, ∑FMC and ∑KBDI can then be compared to ascertain what, if any, influence climate change and/or the SOI may have on these trends (designated *S*). Moving average methods should also provide an indication if new altered states appear arising from any changes (Ives et al, 2012).

A moving average for ∑FFDI≥25 (suggested by Lucas et al, 2007) (or ≥50) was also assessed along with ∑FMC and ∑KBDI. This should also provide some indication of the effects of climate change or SOI. As ENSO periods do not last 4years , the effects of ENSO can be determined within the 4 year trended data, rather than an annual averaging period.

5.6.5 Moving GEV

Gumbel (1958) and Kotz and Nadarajah (1999) identified that for EVA techniques, a sample size of 7 provides a practical minimum from which recurrence values of parameters of interest can be determined, however, this potentially attracts significant errors.

Where data has gaps in annual maxima or is less than 8 years in record, the best-linear estimators, such as the Leiblein Best-linear Unbiased Estimator, or Leiblein BLUE (Jeary and Slack-Smith, 2008), can be used. This technique uses correction factors in tables (Kotz and Nadarajah, 1999). Such a technique is both more complicated and lack accuracy when compared to the EVA techniques discussed in section 5.5.2 above (Gumbel, 1958).

The size of 20 years of data, however, allows for a suitable degree of accuracy (0.95) for recurrence periods of 28 years which is only marginally increased with increasing sample years(Gumbel, 1958). The degree of accuracy (referred to by Gumbel (1958) as the *Maximum Probability of Most Probable*) increases marginally to 0.97for a sample size of 35 years and 0.98 for a sample size of 45 years. Sample sizes of 35 plus are best for a 50 year recurrence, although 20 years of data can still be extrapolated for 50 year recurrence levels. It can be seen therefore, that for the current study, the use of a minimum of 20 year sample size is necessary.

Coles (2004) identifies that randomness in the generation of data induces randomness in the estimator, and as such there may be bias associated with sampling. The sampling distribution therefore determines the variability of the estimator and hence bias. A measure of the extent of bias is the as the standard error of estimate (referred to as standard error or S.E.). The standard error of estimate is related to regression analysis in that it typically provides an estimate of the dispersion of the prediction errors when you are trying to predict Y values from X values in a regression analysis. As such, for EVA techniques, the standard error will also be considered, as a lower S.E. gives a more precise estimator. However, sample sizes of 30 or more are considered minimal for statistical purposes and hence the use of standard errors for such small samples must not be relied upon. In that regard, for regression, the best measure of error is the correlation coefficientr^2.

By applying the principles of moving averages described in section 5.6.4 to the EVA assessment methodology, it is possible to consider likely climatic changes in fire weather, notably for the three parameters of FFDI, FMC and KBDI.

The method applies a suitable EVA approach to the first 20 years (years 1-20) of data for a parameter, recording the EVA_{50} result, and then shifts by 1 year, to the next 20 years of data (i.e. 2-21), and so on (3-22, 4-23, ...) until all data has been assessed and EVA_{50}results obtained. The resultant points are plotted (linear) using bar charts with S.E and trend lines. The trend lines are measured with the slope parameter (designated *S*) providing the overall trend associated with climate change.

This can only be achieved where there are sufficient years of data. The NSW Historical dataset only provides 21 years of data, hence will not be a suitable dataset, however, the National Historical dataset, comprising 8 weather stations identified by Lucas et al (2007) has a period of 43.5 years, providing 23 plotting positions for the period 1972-2015.

As the National Historical data commences on 1 June (1972), this will also provide a seasonal, rather than calendar assessment.

5.6.6 Filtering through percentile analysis of FFDI

Percentile assessments are a simple metric which is commonly used in climatic studies, particularly where longer time-series data is available (Hasson, 2009). Where datasets are less than 50 years, then it can be difficult to ascertain the full extent of *extreme* fire events since key events might have occurred prior to the dataset, or are yet to be observed in the record. Under the influence of climate change, such a record may not have been observable previously.

Percentile values may be useful where the key fire weather threshold values have been determined. A threshold of FFDI≥12 has been used for considering safety of the community for prescribed burning (RFS, 2002), whereas the threshold of FFDI≥25, has been suggested when considering fire season (Lucas et al, 2007) or when annualised for trends in climate change (Hennessey et al, 2005). Clarke et al (2011), considered that FFDI>40 was suitable to illustrate changes in fire season over regional landscapes (see Chapter 4). This threshold appears to be based on the misunderstanding of the bushfire danger period as relating to house losses, where it is more related to operational bushfire control thresholds. Such a high threshold of FFDI>40 may be suitable for illustrating shifts with climate change, and these may be similar for lower FFDI thresholds (such as FFDI>25) but cannot be used as a suitable indicator of shifts in the actual bushfire danger period or prescribed burning conditions. As discussed previously, Lucas et al (2007) considered a better benchmark of FFDI≥25 as a more appropriate condition of considering changes in seasonal FFDI.

When considering the EVA of component parameters within FFDI, and for ascertaining wind aspects for DEFFM calculations, high wind threshold for FFDIs less than 12 would provide a basis for filtering non-fire weather days (such as winter), which could otherwise affect any EVA assessment for design wind conditions. This may also apply in relation to temperature (Tmax) and relative humidity.

An alternate approach is to use the same FFDI days (i.e. maxima ranked FFDI within the record), as the filter and assess wind, temperature and humidity values within the dataset and re-rank data on those specific parameters, rather than FFDI. Although this may be useful for comparison, the nature of DEFFM is that a filter of FFDI ≥12 or ≥25 as a threshold would be more suitable, and provide less bias than other approaches.

5.6.7 Correlation assessment for SOI and fire weather parameters

Correlation assessments quantify the degree of relationship which exists between variables. Simple correlation allows for an efficient means of assessing covariance between two variables. If fire weather is independent of SOI, the Pearson's correlation coefficient (r) will approach zero (0). If the correlation is strong, the r value will approach

1. A relationship can either be direct (both parameters increase) or inverse (one will increase as the other decreases - represented with a negative sign).

Where an ENSO event is considered then an overall moving average can be applied to the bushfire danger period within a year and each year compared in succession with a fire weather parameter (similar to that of Crompton et a, 2010). In chapter 4, we identified that the SOI is highly variable but is trending slightly to more positive (i.e. wetter) conditions over the period of measurement. The correlation for this trend however, is likely to be low. While this provides a degree of visual representation, it does not provide a statistical basis upon which to ascertain likely relationships (i.e. between SOI and fire weather).

However, a more robust approach, would be to determine what, if any correlation exists between SOI, and fire weather parameters such as FFDI, FMC and KBDI so as to establish whether any changes are associated with temperature and relative humidity (FMC), drought (KBDI) or multiple factors (FFDI). As such, a Pearson's Correlation can be made measuring the *r* value for SOI vs. FFDI, SOI vs. FMC and SOI vs. KBDI.

By comparing the SOI data using simple correlation techniques with monthly ∑FFDI, ∑FMC and ∑KBDI, the likelihood that SOI is a significant confounding factor in relation to possible climate change, and changes in fire weather can be ascertained.

5.7 Summary

For the current study, there are 21 fire weather areas which cover NSW (excluding Lord Howe Island) and the ACT. Representative weather stations and vegetation distributions within these fire weather areas has been identified and using GIS vegetation classes have been distributed within those fire weather districts. The average maximum fuel characteristics have been calculated for forest and grassy woodlands. For the FFDM5 equations, fuel loads will be used (for rate of spread and flame heights) and fuel hazard scores and elevated fuels will be used for DEFFM equations.

Of the 21 fire weather districts, it was found that 18 fire weather districts have a significant distribution of forests and grassy woodlands. These 18 fire weather districts will form the basis of assessment of EVA_{50} fire behaviour values using the FFDM5 and DEFFM models.

To develop a suitable design bushfire scenario for planning and construction practice purposes, and to consider climate change implications, it will be necessary to assess the fire weather and fuel moisture of each site using *extreme* value techniques. The techniques to be tested are the GEV_{50}, $Amax_{50}$ and GPD_{50} methodologies.

From the discussion in section 5.5 and 5.6 above, there are four clear approaches for assessing both design bushfire and the effects of climate change and/or SOI on trends in fire weather parameters (FFDI, FMC and KBDI). These approaches include:

(i) the application of suitable EVA approaches (i.e. GEV_{50}, $Amax_{50}$and GPD_{50}) to suitable fire weather parameters (e.g. FFDI, FMC and KBDI). This may also involve some filtering of data in relation to temperature, humidity, wind speed/direction and drought.

(ii) the use of a 4 year moving average will be applied to annual and seasonal cumulative values for FFDI, FMC and KBDI to ascertain any trends over the period of data (1972-2015).

(iii) Annualised threshold exceedance over a moving 4 year period for FFDI, FMC and KBDI.

(iv) Pearson's Correlation approach applied to monthly SOI and compared to monthly $\sum$FFDI, $\sum$FMC and $\sum$KBDI, so as to determine likely influence of SOI on these fire weather parameters.

(v) 20 year moving GEV_{50} to ascertain the impacts on fire weather parameters at the *extreme*.

Figure 5.3 below provides an overview of the research methodology proposed.

Chapter 6 provides the results and a discussion of the preliminary *extreme* value assessment of fire weather conditions including FFDI, average wind speed (and direction), temperature and humidity, KBDI and fuel moisture content. This will provide an assessment comparing the fit of data to the three different *extreme* distributions (Gumbel, GEV and GPD) as well as considering preliminary work on FFDI by Louis (2014).

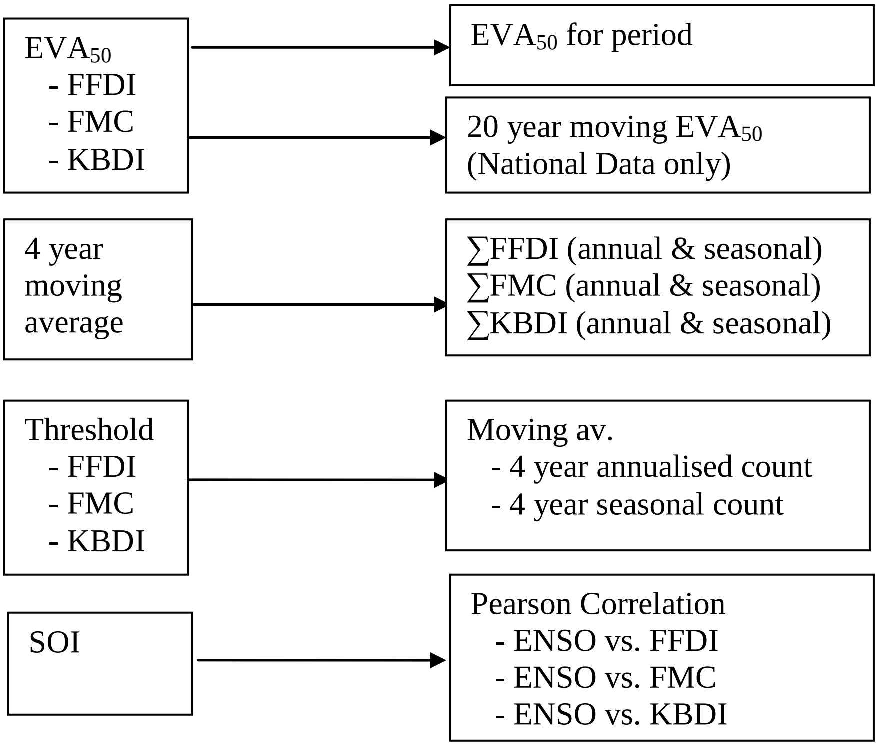


Figure 5.3: Research Methodology Flowchart

Chapter 7 provides a synthesis of the resultant assessment and applies the appropriate fire behaviour models for comparable fire behaviour outcomes (e.g. rates of spread, flame heights), as well assessments of trend of FFDI, FMC and other parameters for adaptive planning purposes.

In Chapter 8, the trends and implications of climate change on land-use planning and construction practice will be assessed using 4 year annualised ∑FFDI, ∑FMC and ∑KBDI, 4 year moving threshold values (FFDI, FMC and KBDI), 20 year moving average for GEV_{50}, and comparative correlation assessments of monthly ∑FFDI, ∑FMC and ∑KBDI with monthly SOI.

CHAPTER 6 - ASSESSMENT OF *EXTREME* FIRE WEATHER INDICATORS FOR NSW

6.1 Introduction

In this chapter the results of the analysis of available weather data are presented and discussed. The data and methodology is discussed in Chapter 5 using the three *extreme* value analysis methods of generalised extreme value (GEV), annual maxima (Gumbel) and generalised Pareto distribution (GPD). The 95th percentile (95%) values of filtered FFDI (FFDI $\geq$12,or equivalent to FDR=High or greater) are also considered. Fuel moisture content and associated recurrence are also assessed using GEV approach. In addition, the chapter considers the basic statistical characteristics of drought over the period of record, as well as wind speed and direction, and temperature and humidity conditions as drivers of fire weather.

This chapter will need to ascertain:

1. Which of the three *extreme* value assessment methods (GEV, GPD or Gumbel) is the most suitable for assessing recurrence for FFDI and FMC?

2. How wind speed and direction impact on the climatology of fire weather in NSW and as a component of the design bushfire for planning and construction practice?

3. Is the relationship for *extremes* the same for drought indicators (KBDI) as it is for FFDI and FMC as the underlying driver of fire weather?

4. If FFDI can be used as a filter of fire weather conditions when considering the climatology of fire weather components, such as maximum temperature and relative humidity?

5. If the two forest fire behaviour models (FFDM5 and DEFFM) compare using the same vegetation and fire weather conditions(notably wind speed and FMC) in resolving design bushfire conditions for planning and construction practice?

6.2 Assessment of Fire Weather Dataset.

The analysis of data was applied to one weather station considered representative of each of the 21 NSW (and ACT) fire weather district used by the Bureau of Meteorology and NSW Rural Fire Service (RFS, 2006). These 21 weather districts are shown in Figure 6.1 below with 10 locations corresponding to the weather stations available from the National Historical Fire Weather Dataset.

Figure 6.1: NSW fire weather districts and key weather station locations (Source: BoM website).

In the case of the Greater Sydney Region (District 4), two weather stations (Sydney Airport and Richmond airbase) were initially used for comparative purposes (of FFDI), so as to ascertain any significant difference in terms of geographical spread.

As a preliminary assessment, the 10 weather stations of the National Fire Weather Database (outside of the western districts) were investigated in terms of mean, 90%, 95%, 99% and maximum values. The percentile values for 3:00pm summer FFDI at the 10 stations (identified in Figure 6.1) are also compared with the current AS3959-2009 policy level (assumed as 1:50 year recurrence levels) in Table 6.1.

From Table 6.1, it can be seen there are substantial differences between the mean and all percentile values from the maximum recorded value and the policy setting of AS 3959-2009.

Table 6.1: Statistics of 3:00pm summer FFDI at 10 NSW weather stations (data generally from 1972-2009) compared to AS3959-2009 policy FFDI values

Weather Station (district)	FFDI					
	Mean	**90%**	**95%**	**99%**	**Maximum**	**AS3959**
Sydney (4)	5.7	12	18	41.3	95	100
Richmond (4)	8.1	21	28	45.2	96	100
Williamtown (3)	6.5	15	22	46	99	100
Coffs Harbour (2)	2.5	6	8	12	95	80
Casino (1)	4.8	11	15	30	101	80
Canberra(8)	11.7	27	34	51	99	100
Wagga Wagga(17)	18	36	45	65.4	138	80
Nowra (4)	5.3	11	19	46.8	120	100
Dubbo (10)	14	29	36	51	99	80
Moree (12)	15.5	28	34	46	125	80

A preliminary assessment of the frequency distribution of FFDI of a sample site was also undertaken from the National Historical Fire Weather database. As summer is the most likely season for *extreme* FFDIs, and for illustrative purposes, a frequency distribution of summer data was undertaken for Sydney airport and is typical of all station FFDI data within the current study. It was noted that some *extreme* events are likely to occur outside the summer period, notably during spring when wind speeds are higher. Figure 6.2 shows the summer frequency distribution curve for the data from Sydney Airport, which has the most comprehensive and intact data in the current study.

This preliminary assessment is important when considering the likely effect of gaps in other station data, as should gaps be likely at the higher or more extreme end of the dataset, this could bias the results significantly.

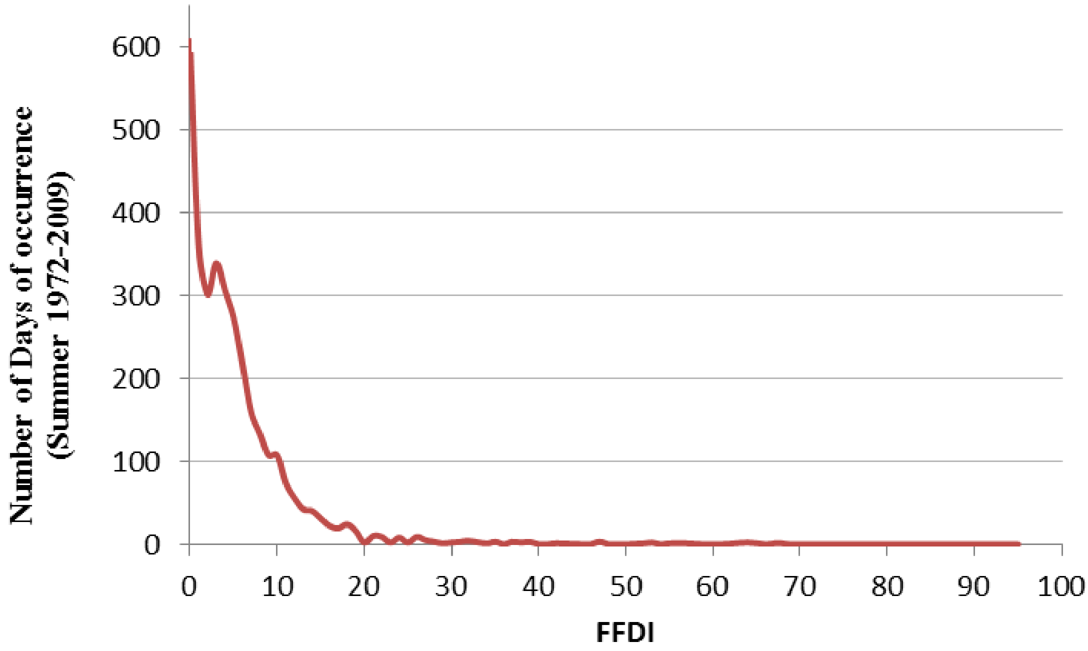


Figure 6.2: Summer frequency distribution curve for FFDI Sydney Airport data 1972-2009

The summer cumulative distribution curve (Figure 6.3) illustrates that the use of average values for weather conditions (FFDI or fuel moisture) has a substantial skew of the data to lower values. This is expected as fire weather conditions are not normally distributed but rather Poisson distributed. The maximum value in the Sydney data is an FFDI of 95 (see also Table 6.1).

Tables 6.1 and Figures 6.2 and 6.3 clearly indicate that approximately less than 1% of the data is likely to be in excess of FFDI 50, making gap filling important, but not critical in terms of likely bias. However, while the assessment of GEV and Annual maximum may not be affected, there could be implications for the GPD approach and percentile assessments which relies on the distribution of lower value data points when assessing for *extreme* values.

As a result of this consideration, it became apparent that two sites, Richmond (Greater Sydney) and Casino (Far North Coast), had significant gaps in the dataset. In the case of Richmond, Sydney airport was preferred, although as seen in Table 6.1, Richmond has a higher set of values than the more coastal Sydney site. A preliminary assessment was undertaken using all three EVA approaches for each of the 10 sites in the National

Historical Fire Weather Dataset (Table 6.1), subsequent assessments used Grafton from the NSW dataset and removed Richmond from consideration.

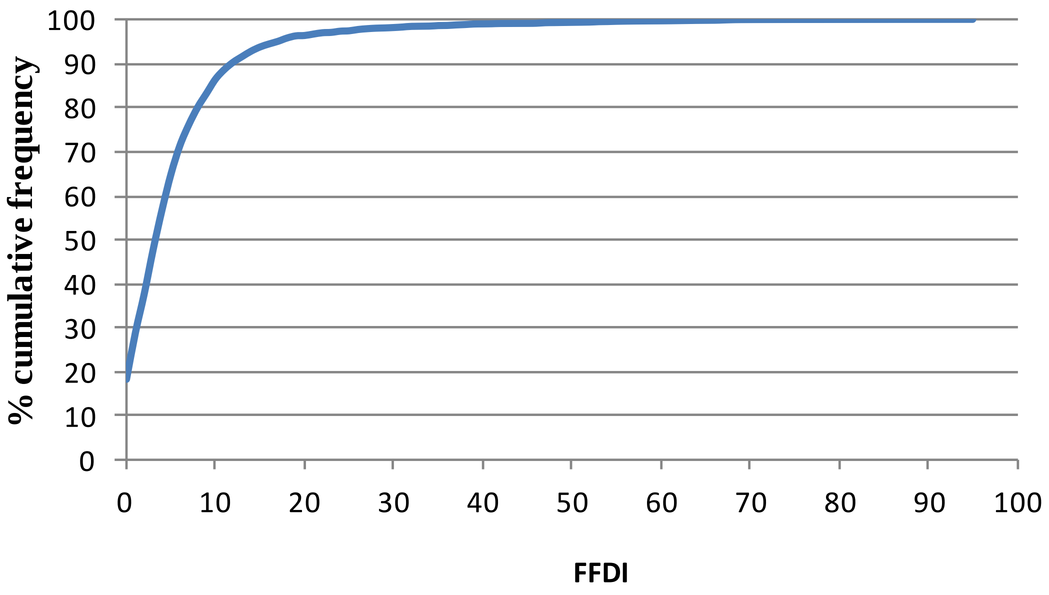


Figure 6.3: Summer percentage cumulative frequency distribution curve for FFDI Sydney Airport 1972-2009

The percentage cumulative frequency is the running total of percentile values and indicates the percentile of FFDI values which fall below that value.

6.3 Assessing Best Fit Conditions of Data to *Extreme* Value Distributions

It can be seen that from the above graph, that approximately 10-15% of the summer FFDI for Sydney airport is greater than 12. There are likely to also be FFDIs greater than 12 in seasons other than summer, although significantly less. It was concluded that a more comprehensive review of the data should therefore be undertaken, having regard to annual, rather than a single season (summer). Histograms, or the normalised frequency of FFDI values were also developed from the data of all stations and these histograms were fitted with the aforementioned three *extreme* value approaches using the EasyFit^{TM} software (Schittkowski, 2002).

An example of such a histogram and the fitted three distributions (i.e., GEV, GPD and Gumbel) are shown in Figure 6.4 for Sydney. In all three of the probability density distribution functions, variable *x* represents FFDI.

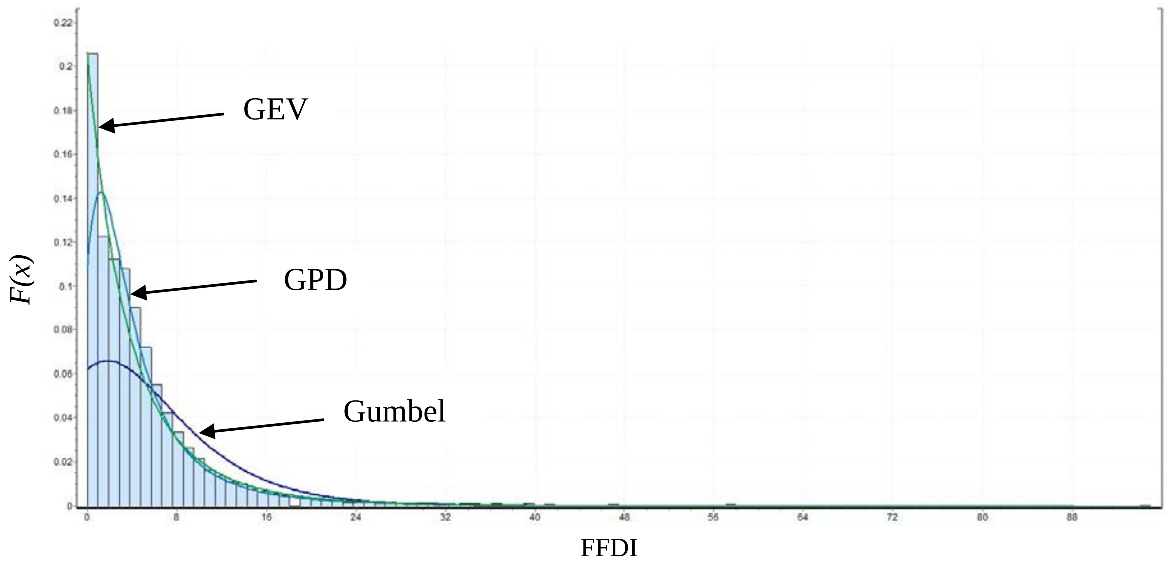


Figure 6.4: Normalised histogram of FFDI for Sydney Airport 1972-2009 and the fitted GEV, GPD and Gumbel probability density distribution functions

So as to compare the frequency of observed data, 'goodness of fit' testing of the data was undertaken with the three identified *extreme* value distributions (i.e. GEV, GPD or Gumbel).The three fitting tests used were:

- Kolmogorov-Smirnov (K-S) Test,
- Anderson-Darling (A-D) Test, and
- Chi squared Test (χ^2).

The Kolmogorov-Smirnov (K-S) test is based on the largest vertical differences found within the dataset between the theoretical and empirical data for each distribution tested (Schittkowski, 2002). Mehrannia and Pakgohar (2014) suggest that this test is commonly used to test goodness of fit, although Schittkowski(2002) indicates that the Anderson-Darling (A-D) test is a more suitable fit to the data as the tail (of the data) is longer (as in *extreme* values). The Chi-squared test is also commonly used to compare the frequency of observed data with asymptotic data and the Poisson distribution (Reiss and Thomas, 2007a). Kotz and Nadarajah (2000) reporting on other studies, recommended the A-D statistics coupled with least squared estimation. However, they also noted and supported the use of the correlation coefficient for the regression of the plotted data used for the *extreme* value assessments. This is discussed further below.

Each test was assessed and ranked against the 'best fit' of the FFDI weather station data using EasyFit™ statistical software as described by Schittkowski (2002) and Mehrannia and Pakgohar (2014) and the results are shown in Table 6.2. A ranking of 1 indicates a best fit, whereas a 3 indicates a least fit of the data. A lower average score, indicates an overall better fit than higher averages.

Table 6.2: 'Goodness of Fit' rankings of three statistical tests against three *extreme* value assessments for FFDI using EasyFit ™ software

Weather Station	K-S			A-D			χ^2		
	GEV	**GPD**	**Gumbel**	**GEV**	**GPD**	**Gumbel**	**GEV**	**GPD**	**Gumbel**
Grafton	1	2	3	1	3	2	1	n/a*	2
Coffs Harbour	2	1	3	2	1	3	2	3	1
Williamtown	1	2	3	2	1	3	1	2	3
Sydney Airport	1	2	3	1	2	3	1	2	3
Nowra	1	2	3	1	2	3	1	2	3
Batemans Bay	1	2	3	1	3	2	1	n/a	2
Cooma	2	1	3	1	3	2	1	n/a	2
Canberra Airport	2	1	3	2	1	3	2	1	3
Goulburn	2	1	3	1	2	3	1	n/a	2
Bathurst	2	1	3	1	3	2	1	n/a	2
Armidale	1	2	3	1	3	2	1	n/a	2
Tamworth	2	1	3	1	3	2	1	n/a	2
Moree	2	1	3	2	1	3	2	1	3
Coonamble	2	1	3	1	3	2	1	n/a	2
Dubbo	2	1	3	2	1	3	2	1	3
Young	2	1	3	2	1	3	2	1	3
Wagga Wagga	2	1	3	2	1	3	2	1	3
Deniliquin	2	1	3	1	3	2	1	n/a	2
Hay	2	1	3	2	1	3	2	1	3
Mildura	2	1	3	1	3	2	1	n/a	2
Cobar	2	1	3	2	1	3	2	n/a	1
Average score	2	1	3	1	2	3	1	-	2

* n/a: not applicable.

All available daily data for the period of the dataset was tested, recognising some stations had gaps and/or filled data (see section 5.3).

The χ^2test has some n/a results for GPD due to the smaller sample size for values of FFDI>12 for these sites.

From the results in Table 6.2, it can be seen that the Gumbel distribution attained the lowest rankings (high values) on all three goodness of fit tests for most weather stations, indicating that it is the least suitable description of probabilistic characteristics of FFDI. Importantly, for the Anderson-Darling Test, the GEV distribution performed best. Of note, is that while the GEV method is preferred, the GPD method has higher rankings in western NSW over the areas closer to the coast (refer to Figure 5.1). These western areas are more likely to have grassland or scrub/shrubland environments (see Chapter 3, Figure 3.3) and hence forest fire danger index will be less relevant than the grassland fire danger index (see Chapter 2) for areas further west. For the Chi squared test, a number of GPD assessments were identified as being not applicable (n/a) by the program (arising from sample size). The above analysis confirms that GEV is more suitable overall, although GPD should also be useful in many cases.

For testing the Null hypothesis (H_o), alpha (α) values of 0.05 and 0.01 have been used to determine whether to accept or reject the hypothesis that the estimated distributions from the data is the true or good description of the expected distribution. At both 95% and 99% confidence limits, the Null hypothesis was rejected for all weather stations for the complete data set available. This arises from the large number of low value FFDIs in the dataset (see Figure 6.4) which is considered as ‘noise’. The use of confidence limits of the mean values for non-normal distributions is problematic and cannot be readily justified (Coles, 2004). For distributions with a heavy tail, the χ^2 test can normally be used for determining confidence limits but the skew associated with the FFDI data, combined with the high proportion of values below FFDI>12, makes such a measure unreliable (Kotz and Nadarajah, 2000).

For all values of FFDI>12, the Null Hypothesis was tested and accepted at p=0.01 for both GEV and GPD distributions however, the Gumbel distribution did not meet the test of significance at p=0.01 or 0.05. Again, Figure 6.4 illustrates the problem of data selection for the three *extreme* value assessment techniques, with GEV and GPD following closely with the theoretical distribution, whereas the Gumbel distribution is not.

As such, the use of confidence limits cannot be used as an adequate measure of suitability of the three distributions (i.e. Gumbel, GEV and GPD) considered.

An assessment of the Coefficient of Variation (CV) was also completed for each dataset. The CV values for FFDI cluster around a value of 1, indicating relatively high variability of the FFDI distribution around the mean. This is reported here for completeness however further results are not presented for the reason discussed above.

Kim et al (2008) suggested that in addition to Kolmogorov-Smirnov and chi-square test, the probability plot correlation coefficient test (*r* values) is also powerful and a relatively easy test for fit in generalised Pareto distributions and has also been used for Gumbel, Weibull and GEV distributions. The correlation coefficients for the plotted data, as r^2, have therefore been included in the assessment and consideration for suitability. Higher correlation coefficient values suggest greater confidence in the distributional fit.

6.4*Extreme* Value Assessments of Forest Fire Danger Indices

The determination of Forest Fire Danger Indices (FFDI) is described in Chapter 2 and is used as a major input for determining bushfire attack levels (AS 3959-2009) or asset protection zones (RFS, 2006). The policy settings for identifying the appropriate FFDI values are given by the NSW Rural Fire Service (2006) as a 1:50 year return period (RFS, 2006). The policy documentation however, does not specify the methodology to be adopted, or the dataset requirements for determining such a value. In the absence of such guidance, three approaches (GEV, Gumbel and GPD) have been undertaken for determining the 1:50 year recurrence. In addition, the preliminary National and NSW datasets have differing periods of data, being 37.5 and 16 years respectively. As will be discussed in Chapter 8, these datasets were subsequently updated to 44.5 and 21 years respectively, but was not available until after this preliminary assessment was completed.

A comparison between the preliminary results of each of the three methods is provided below.

6.4.1 Results

An example of the graphical representations for the three techniques are shown in Figures 6.5 - 6.7. It can be observed that GEV (Fig 6.5) produced the best regression model over that of GPD (Fig 6.6) or Gumbel (Fig. 6.7) due to the higher correlation coefficient values (r^2), although all values are considered acceptable. The latter also has the lowest correlation coefficient, although all are considered as having relatively high correlations.The determination of the return period FFDI values using GEV,GPD and

Gumbel distributions, including their correlation coefficients, shape and intercept values are provided in Appendix 4 for each weather station used in the analysis.

Figures 6.4, 6.5 and 6.6 provide examples of linear-log plots of FFDI *vs* recurrence for the Sydney weather station, which is located within the Greater Sydney Fire Weather District (NSW RFS, 2006). The plots were then subject to a regression using the log-linear function as expressed in Eq. 5.3.

The resultant lines of best fit are included in Figs 6.4, 6.5 and 6.6 respectively and can be extrapolated out to the 50 year recurrence values.

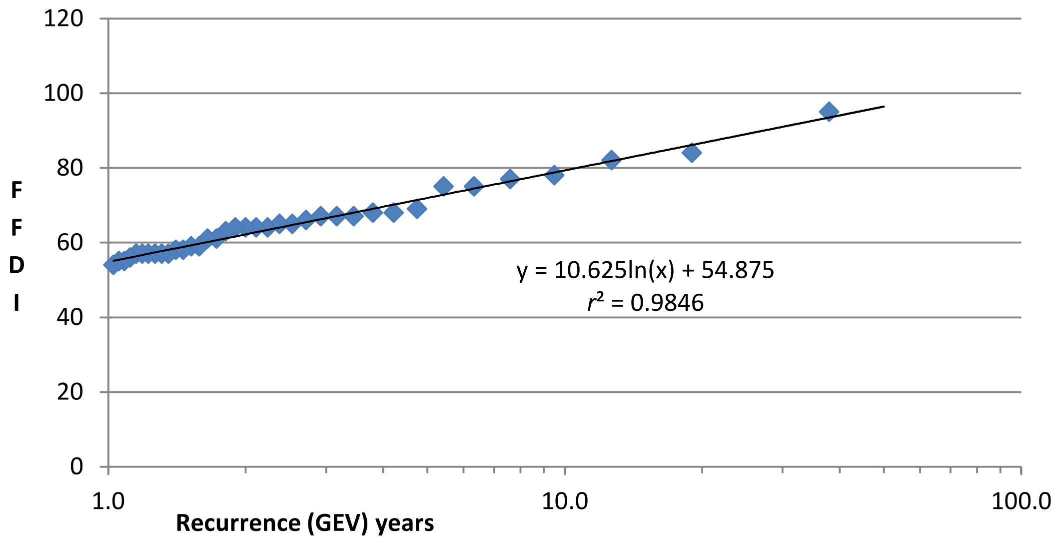


Figure 6.5: FFDI GEV assessment for Sydney Airport (line represents regression)

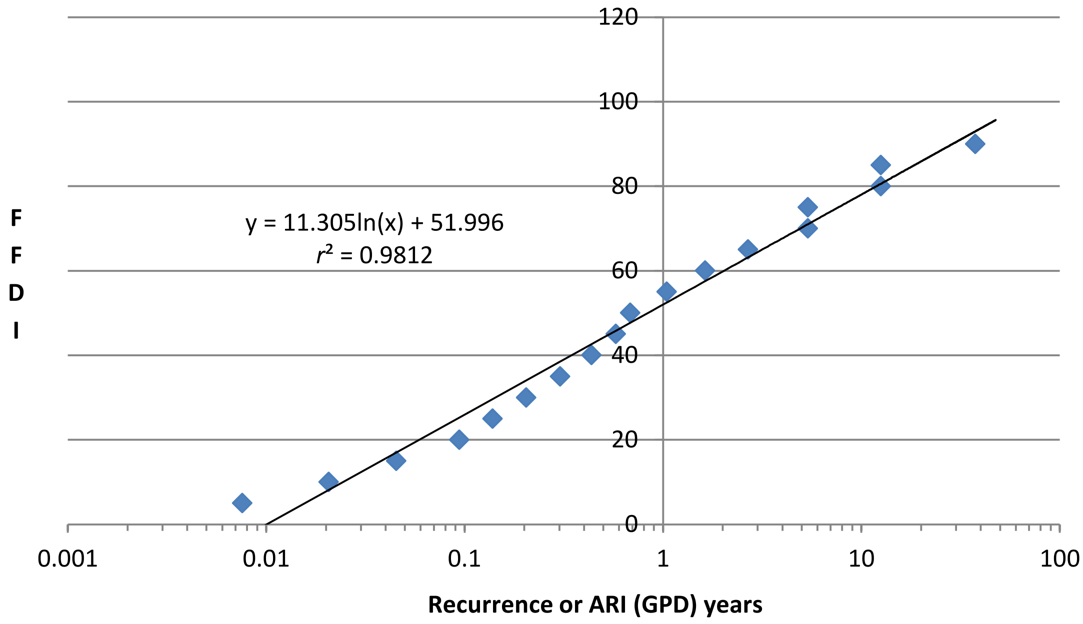


Figure 6.6: FFDI GPD assessment for Sydney Airport (line represents regression)

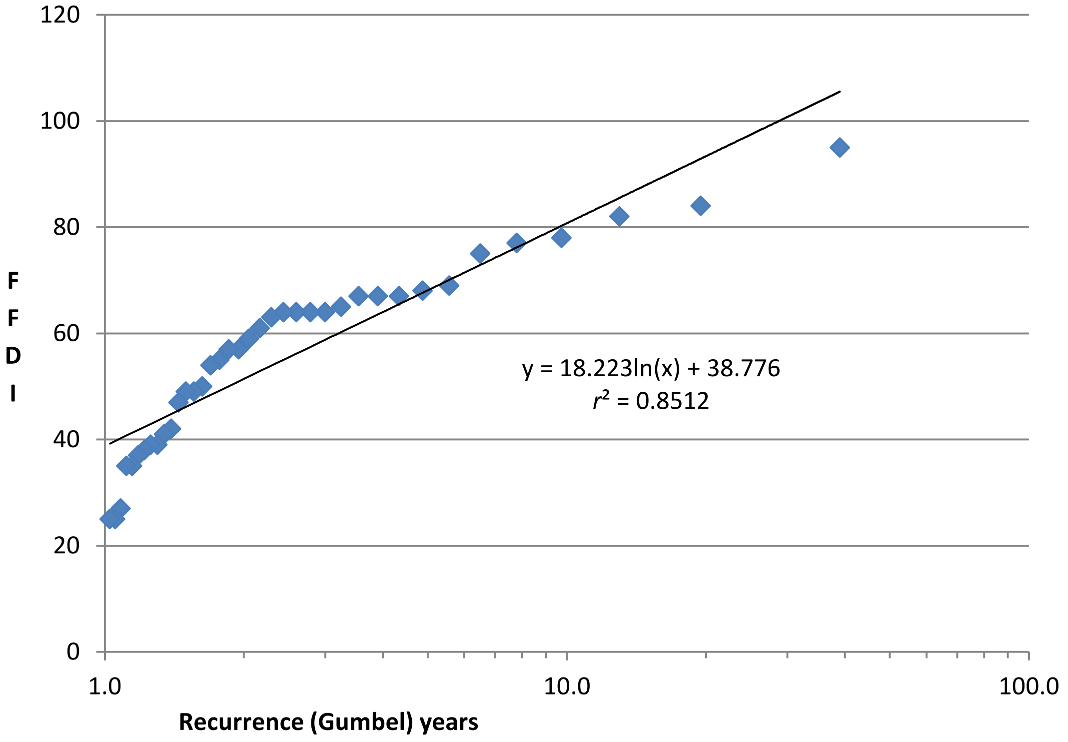


Figure 6.7: FFDI Gumbel assessment for Sydney Airport (line represents regression)

A summary of these results based on the three methods of 1:50 year return period, filtered 95 percentile values (where FFDI≥12), the policy setting within AS3959 (2009) and previously reported GPD and Gumbel values (Louis, 2014) for selected weather stations in all NSW weather districts is provided in Table 6.3 below. The maximum recorded values are also included in this table for comparison.

In the case of weather stations within the National Fire Weather dataset, 37.5 years of data was used, whereas for those stations within the NSW Fire Weather dataset initially only 16 years of data. Although the assessment has been undertaken for all weather areas, it is noted that areas in the western parts of the State do not have forest vegetation (including rainforests and grassy woodlands) present. In such cases the use of a GFDI assessment would be more appropriate but is beyond the current scope of this study.

The plots for each of these sites are provided in Appendix 5.

Casino was initially assessed with 24 years of data, however it was found that although Grafton had a smaller number of years (21 years), the Grafton site had a more complete record. A comparison between the 1:50 year recurrence results for Grafton and Casino can be found at Table 6.3.

Table 6.3: Comparative design FFDI based on various methods (1972-2009)

Fire Weather District No. and	1:50 year Recurrence FFDI			Other design FFDI			Louis (2014) #	
Weather Station	Gumbel*	GEV	GPD	95%	AS3959	Max	Gumbel	GPD
1. Casino	143	120	116	na	80	101	na	na
Grafton	120	101	94	37	80	93	84	(88)
2. Coffs Harbour	94	95	82	34	80	95	86	90
3.Williamtown	121	105	101	45	100	99	102	103
4. Sydney	110	96	96	45	100	95	93	94
Richmond	128	112	108	n/a	100	96	95	108
5. Nowra	122	112	104	47	100	120	105	101
6. Batemans Bay	112	97	90	42	100	74	na	na
7. Cooma	96	83	84	39	80	68	80	(84)
8. Canberra	115	102	96	42	100	99	104	92
9. Goulburn	121	105	104	50	100	91	na	na
10. Bathurst	100	83	82	37	80	91	na	na
11. Armidale	52	46	46	24	80	46	na	na
12. Tamworth	101	100	100	40	80	105	na	na
13. Moree	104	102	103	36	80	125	102	101
14. Coonamble	163	123	121	42	80	121	na	na
15. Dubbo	121	107	101	40	80	99	105	102
16. Young	97	79	89	41	80	71	na	na
17. Wagga Wagga	144	128	121	47	80	138	127	119
18. Deniliquin	146	131	125	51	80	121	na	na
19. Hay[1]	125	126	106	36	80	125	113	106
20. Mildura[1]	150	133	130	49	80	132	128	136
21. Cobar[1]	128	114	113	44	80	117	104	109

*1:50 year Gumbel based on calendar year

#1:50 GPD based on National Historic Fire Weather database but Gumbel based on extended BoM data for June-July period.

Bracketed values also based on extended BoM data. 95% values are for summer period only.

1 - data for GEV_{50} drawn from 1972-2009 period, GPD and Amax drawn from 1972-2009, these sites only.

na – not available.

6.4.2 Discussion

In general, there is reasonable agreement between the use of GEV and GPD assessment approaches. Generally, the FFDI values determined by the Gumbel method are noticeably higher in the current study than the Louis (2014) Gumbel values reflecting the different selection of maximum annual values from the dataset. The difference is largely attributed to the use of calendar years in the current study, compared to July-June year data selection by Louis (2014).

With some exceptions, the GPD results between Louis (2014) and the current study, compare well, notwithstanding the likely differing determination of peaks over thresholds. Likewise the use of calendar year as against the June-July year provides a number of comparable results using the Gumbel annual maximum approach.

GPD and GEV values are generally close and also compare well with the Louis (2014) GPD results for most districts. The major exception is Moree, where the current study Gumbel and GPD values approximates the Louis (2014) Gumbel and GPD values, and the GEV_{50} value of the current study is significantly higher. Although not always exactly the same, the Louis (2014) values (using a GPD approach) correspond closely with this study's results with three (Cooma, Richmond and Hay) stations having the same value and one (Dubbo) within one FFDI value and another four within two FFDI values (Williamtown, Sydney, Moree and Wagga Wagga). These can be attributed to the different approaches to peaks over threshold determination used in the respective studies.

A comparison was undertaken between the GEV_{50} and the GPD_{50} values for each of the 21 weather stations and plotted as a Q-Q plot in Figure 6.8. Table 6.3 is the source of the data for this figure. The resultant plot line and regression (with correlation co-efficient) is also provided in the figure. It can be seen that the correlation is very high and a slope of 0.897. The average difference over the 21 sites is approximately 3.7.

For Tamworth all three assessments in the current study converge at FFDI=100.

When compared to the values provided within AS 3959-2009 and RFS policy settings, it is clear that based on the 1:50 year recurrence, some important differences exist with calculated and policy values. Interestingly, the GEV (and the GPD) values are generally in close agreement with the AS3959 and RFS policy settings for Sydney, Williamtown, Canberra, Goulburn, Cooma, Young and Bathurst, but not elsewhere.

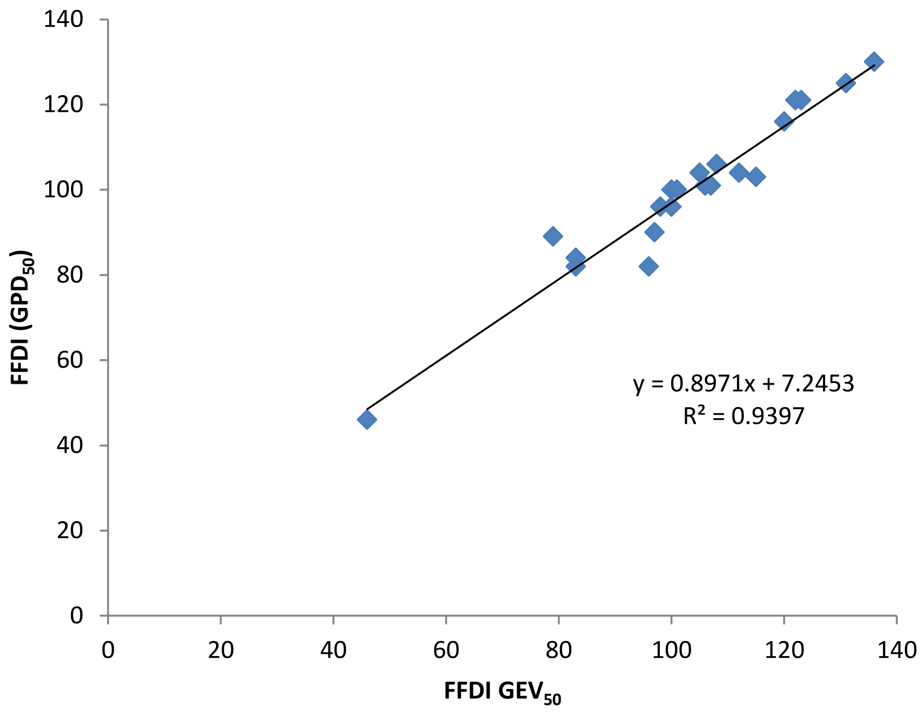


Figure 6.8: Comparative plot of FFDI GEV_{50} and FFDI GPD_{50} values

This is not surprising, considering the previous policy values were estimated from extrapolation (best guessing) from the studies of Hennessey et al (2005). What is more surprising is that so many policy values were as close to actual GEV_{50} and GPD_{50}weather station results in the current study.

As can be seen from Table 6.3, there is a significant gap between the filtered 95^{th} percentile value (originally proposed by Douglas and Tan, 2005) and the maximum FFDI at all stations, indicating that the events corresponding to the maximum FFDI are truly uncommon and generally more closely align with the GEV assessments. Since the high frequency and lower FFDI events or conditions are not of concern in risk based design or policy making, the noise can be ignored in GEV analysis. As such, when using the filtered 95^{th} percentile assessment, even where FFDI>12, this approach will still significantly underestimate weather conditions for design bushfire determination.

The design FFDI values for the far western areas with weather stations at Mildura, Cobar and Hay are significantly underestimated by policy settings compared to the 1:50 year events. As discussed above, these areas do not contain forest or grassy woodland vegetation within their fire weather areas and GFDI or other climatic values, such as wind speed, should be used for such areas.

Armidale is notable in that the policy setting (FFDI=80) significantly exceeds the 1:50 year return values for all three assessment methods, which approximates FFDI=50. Such a large excess of the policy setting over the 1:50 year recurrence values means an ultra-conservative (i.e. higher degree of safety) approach for bushfire protection design. A reconsideration of the current policy setting would be necessary; especially as the fire weather area contains towns with similar elevations over much of this district.

The effect of proximity to the coast is well illustrated by comparing Sydney and Richmond weather stations. Richmond has higher FFDI values across all assessment methods, however, considering the diversity of elevations and land forms in the Sydney Fire Weather Area, the policy setting of FFDI=100 is reasonable.

A comparison of Canberra and Goulburn is interesting as both approximate the policy setting of FFDI=100, are geographically close to each other and share many topographical and land form features. This gives confidence that the policy setting is reasonable for these areas which also extend south from Sydney. Williamtown (at FFDI=106 using GEV_{50} and FFDI=101 using GPD_{50}) which is north of Sydney also provides some confidence that an FFDI=100 is an appropriate setting for much of the coastal and near coastal areas of the Hunter, Central Coast, Sydney and Illawarra areas of the State. Notwithstanding this, it is noted that Nowra has an elevated 1:50 year return period of FFDI=112 using GEV_{50} and FFDI=96 using GPD_{50}.

For northern and western areas of the State, the policy setting of FFDI=80 underestimates the potential impact of bushfire on built assets and planning practice. Assessments for all three methodologies used in this investigation indicates that the policy settings of FFDI=80 for the Northern Ranges (Tamworth), North Western (Moree), and Lower Central Western Plains (Dubbo) are all underestimated on the basis of a 1:50 year return period, and the value of FFDI=100 would be a better policy setting for these areas. Coffs Harbour (coastal location) sits at FFDI=82 using the GPD_{50} method, compared to approximately FFDI=95 for GEV_{50} and Gumbel values, which is conjunction with the Grafton station (GEV_{50}=100) suggests a policy value of FFDI=100 is appropriate.

The results for three areas; Eastern Riverina (Wagga Wagga), Upper Central Western Plains (Coonamble) and Far North Coast (Casino) have values that suggest a 1:50 year return of FFDI=120 would be a suitable policy setting, whereas currently these are FFDI=80 areas.

Overall, the GPD_{50}results of Louis (2014) when compared to that of the current study shows some minor differences, which may be associated with the selection of the threshold values used. These GPD_{50} results are based on the 38 years of Lucas (2010) data for these stations used in the current study (note two exceptions of Grafton and Cooma). The Gumbel values are based on an extended BoM dataset and are seasonally adjusted. As a result most Gumbel values of Louis (2014) vary from those of the current study. The reasons for such discrepancies are related to methodological problems with analysing data using the Gumbel method without seasonality considerations. Gumbel assessment without seasonality adjustments having regard to the poorer fit of data and, when related to bushfire weather, should not be relied upon.

Importantly for all sites, the use of 95% filtered FFDI (>12) values are not suitable guides for determining policy setting for FFDI and Table 6.3 shows that many maximum FFDI values may exceed or underestimate assumed 1:50 year return periods when setting policy values with only a few areas (Williamtown, Canberra and Sydney are notable) closely corresponding to assessed return values. It should be noted that in many cases the years of data may correspond to approximately 38 years (for National dataset), whereas others can have less than 20 years of data (for NSW dataset). The filtered values would still underestimate risk relative to other methods, including maximum values.

6.5Fuel Moisture

Fuel moisture is used in the DEFFM forest fire behaviour calculations (Section 2.2.4). Fuel moisture is derived from daily maximum temperature (^{0}C) and humidity (%RH) for 3:00 pm using Eqs 2.17 and 2.18. and have been used in deriving %FMC from the National and NSW fire weather datasets described in Chapter 5.

Fuel moisture was subjected to GEV, GPD and Gumbel assessments. In addition, average (Av.), standard deviation (S.D.), and 5 percentile (%) fuel moisture values for each fire weather area and associated weather station were also determined. The results of this assessment are considered in section 6.6.1 and Table 6.7 below. Since fuel moisture forms a negative log-linear relationship, the Gumbel assessment is referred to as Amin (rather than Amax) to reflect the minimum RH values used.

Where predictions of FMC fall below 2%, then a base value of 2% is used (see section 2.6.2).

6.5.1 Results

Figure 6.9 provides a graphical representation of the GEV assessment for Sydney Airport. This illustrates the negative log-linear relationship of the GEV approach when applied to fuel moisture content (FMC).

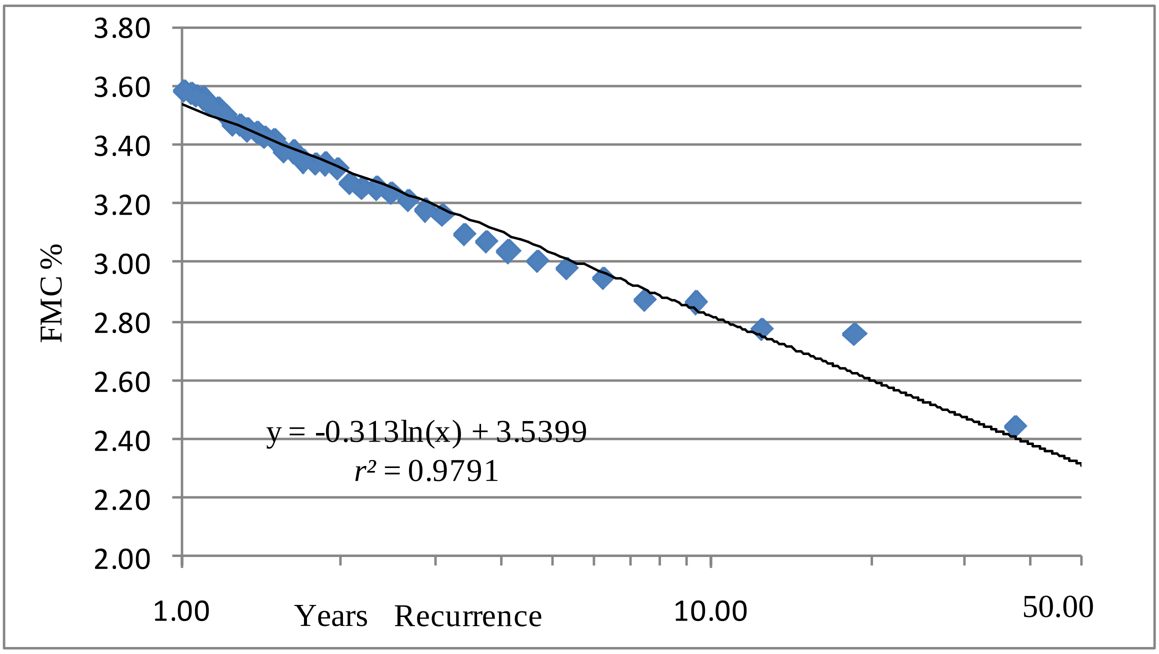


Figure 6.9: Graphical representation of FMC *extreme* value assessment for Sydney Airport (line represents regression).

Table 6.4 provides the results of the assessment of FMC using GEV, GPD and Gumbel(Amin) methods. It also provides the minimum FMC recorded and the filtered averages of FMC (where FFDI>12).

Clearly, the use of EVA methods using the negative expression must be used cautiously. In theory, results could be in the negative domain, however, negative fuel moisture is not possible, and the general 2% FMC limitation should be used. This was most evident when using the Gumbel (Amin) assessment where results are more likely to be lower than 2% in Table 6.4.

Table 6.4: Basic statistics and 50 year recurrence for FMC using GEV, GPD and Gumbel (Amin), assessments (where FFDI>12) for NSW weather stations

Weather Station	FMC 1:50 Recurrence			FMC where FFDI>12		
	A_{min}	GEV	GPD	Min.	Mean (S.D.)	5%
1.Grafton	1.72	2.18	2.59	2.51	6.5 (1.2)	4.2
2. Coffs Harbour	1.61	1.53	2.65	2.26	7.0 (1.5)	4.6
3. Williamtown	1.33	1.92	1.86	2.17	6.5 (1.5)	4.0
4. Sydney	1.94	2.32	2.43	2.44	5.1 (1.0)	3.4
5. Nowra	1.99	2.44	2.22	2.68	6.5 (1.6)	3.8
6. Batemans Bay	2.43	2.85	2.65	3.02	6.4 (1.6)	4.1
7. Cooma	1.15	2.09	1.34	2.26	5.1 (1.4)	3.1
8. Canberra Airport	1.95	2.21	2.39	2.23	5.4 (1.3)	3.5
9. Goulburn	1.85	3.21	1.75	3.36	5.5 (1.5)	3.3
10. Bathurst	0.70	2.30	2.55	2.60	6.5 (2.5)	4.4
11. Armidale	2.15	3.11	3.06	3.38	5.4 (1.0)	3.9
12. Tamworth	2.10	2.57	2.43	2.76	5.9 (1.4)	3.7
13. Moree	1.86	1.90	2.42	1.93	5.4 (1.3)	3.5
14. Coonamble	2.29	1.80	1.95	2.18	5.7 (1.3)	3.6
15. Dubbo	2.18	1.95	2.17	1.98	5.7 (1.4)	3.6
16. Young	1.86	2.15	1.73	2.40	5.4 (1.4)	3.4
17. Wagga Wagga	1.97	3.10	1.96	2.69	5.2 (1.4)	3.2
18. Deniliquin	1.80	2.52	2.22	2.81	5.9 (1.5)	3.6
19. Hay	1.87	1.90	2.40	1.93	5.4 (1.3)	3.5
20. Mildura	2.16	2.09	2.40	2.08	5.6 (1.4)	3.3
21. Cobar	2.18	1.87	2.31	2.00	5.2 (1.4)	3.2

6.5.2 Discussion

In many cases GPD and GEV values align reasonably well, notably Williamtown, Armidale, Tamworth and Dubbo. For $Amin_{50}$, Moree has 1:50 year return periods which aligns well with GEV_{50}, however, overall, $Amin_{50}$ assessments are generally lower than either GEV_{50} or GPD_{50} approaches. In addition, these lower values fall under the critical 2% FMC limit suggested as a limit by previous studies. Bathurst has a very low value (0.7%) for the Amin approach, and cannot be relied upon.

For minimum recorded values, only three sites (Goulburn, Batemans Bay and Armidale) have values in excess of 3% FMC with Armidale being the highest. Mean values are quite high and generally exceed 5% FMC and range up to 7% for Coffs Harbour. 5 percentile values range from 3.1% (Cooma) to 4.6% (Coffs Harbour) FMC.

The graphs for GEV_{50}FMC curves can be found in Appendix 6. These have similar characteristics to FFDI, although overall, there is slightly less correlation than FFDI at the 1:50 year return periods. Overall, GEV_{50} has better correlation coefficients over other methods. EVA correlation coefficients for FMC with shape and intercept parameters can be found in Appendix 7.

6.6Wind Speed and Direction.

Apart from contributing FFDI evaluations for bushfire prone areas, wind speed is also used in determining fire behaviour for grassland vegetation and shrubland/scrub vegetation communities (including mallee) as the design bushfire input parameter in planning and construction practice (Sections 2.4 and 2.5). It is also used as a major direct input into the DEFFM bushfire behaviour calculations for forest fires (see Sections 2.3).

To save confusion when averaging wind speed values, the 10 min mean wind speed will simply be referred to as the ‘wind speed’. Averages of the dataset will be referred to as 'average wind speed'. Data used in the current study is for daily 3:00pm Australian Eastern Standard Time (AEST) and is independent of Eastern daylight saving and approximates adverse daily fire weather conditions (Lucas, 2010).

6.6.1 Wind speed and *extreme* FFDI.

The challenge in examining winds is that *extreme* wind events may well be associated with conditions outside the bushfire danger period or on days with rainfall, storms, non-drought periods, high humidity and/or low temperatures. To determine input values for wind speed when bushfire conditions may be prevalent, wind speed must also be associated with other fire weather parameters, such as high temperature, low rainfall and low humidity.

For the current study, it is proposed to undertake the wind assessment method for bushfire planning purposes used by Long (2006) and consider both wind direction and average wind speeds. This will allow for a fuller consideration of prevailing wind conditions that are associated with adverse fire weather.

Table 6.5 displays the highest seven bushfire weather days (@ 3:00 pm) for Sydney Airport using FFDI and associated fire weather conditions; including relative humidity (RH), wind direction (degrees and bearings) and wind speed, maximum daily temperature, daily drought factor (DF) and Keetch-Byram Drought Index (KBDI).

Table 6.5: Selected top 7 fire weather days recorded at Sydney Airport (3:00pm) with associated fire weather conditions

Date	Daily Conditions			3:00 pm Conditions				
	FFDI	DF	KBDI	T_{max} (^{0}C)	RH %	Direction (^{0})	Direction (bearings)	Wind Speed (kph)
16/12/1979	75	9.2	116.8	40	6	315	NW	31.7
25/11/1982	77	8.3	81.2	43.4	4	270	W	29.5
2/03/1985	78	9.3	121.7	39.2	13	292.5	WNW	44.6
23/12/1990	95	9.8	131.4	41.7	15	270	W	50
24/09/2006	82	7.1	33.7	34.6	13	320	NW	64.8
22/11/2006	75	9.5	111.2	40	8	326	NW	33.5
3/10/2007	84	8.6	49.8	36.2	7	308	NW	46.4

It can be seen from Table 6.5, the highest FFDI day reached FFDI=95 which was largely associated with drought conditions, whereas the highest wind day (64.8 kph) was associated with an FFDI=82. The three lowest wind speeds were all around FFDI=75~77.

As house losses and loss of life are most likely to occur when FFDI≥50 (Blanchi et al, 2010), this threshold value may be used as a basis for filtering out wind including the high winds that are not associated with bushfire events. This was the approach of Long (2006) although she included both grassland and forest fire danger indices.

The role of associated wind direction accompanying wind speed has been discussed in Chapter 4.

The raw wind direction data was recorded on the basis of 16 discrete wind directions for the National Fire Weather Database, whereas the NSW Fire Weather Database used 360^0 wind directions on a continuous scale. The NSW database was converted into the16 notional discrete directions before further analysis, so as to provide continuity with the National Database.

Two other additional data entries are zero wind speed or "CALM" conditions and missing records. CALM conditions were not observed where FFDI>25. Where there was missing wind speed/direction, the FFDI could not be determined. In all therefore, while it is possible for there to be 18 combinations associated with wind conditions, there were only 16 associated with FFDI≥50 or with the sample used to derive GEV curves.

6.6.2Basic statistics of the 10 minute wind speed

Maximum, average and standard deviation of recorded wind speeds for FFDIs ≥50 for all sites can be seen in Table 6.6 below. This table presents the summary of highest mean wind speed recorded, average of the 3:00pm wind speeds and the standard deviations for each of the 21 weather stations in NSW and the ACT.

Care should be exercised in the use of an average of the wind speed values which may not be suitable for design bushfire considerations, if wind speed data can also be assessed considering *extreme* value approaches. These issues are further discussed in 6.5.2 below.

As expected, sample sizes increased with distance from the coast. Inland, notably far western locations had the highest number of days with FFDIs>50. This reflects their dry and hot environments. The western sites of Wagga Wagga, Young, Hay, Deniliquin, Dubbo and Cobar all have relatively flat topographical features. They also have lower average wind speeds, suggesting that factors other than wind were likely drivers of FFDI.

Other weather stations generally recorded sample sizes of FFDI equal to or greater than FFDI 50 ranging from 30 to 69. Cooma and Bathurst sample sizes with FFDI>50 were exceptions recording only sample sizes of 19 with 15 respectively.

Batemans Bay, due to its coastal location exhibited the highest wind speed and highest average for the filtered FFDI. Sydney Airport and Williamtown, both of which have coastal locations have lower maximum and filtered wind speeds.

Table 6.6: 3:00pm wind speed conditions (at FFDI>50) for 21 NSW weather stations

Fire Weather District No. /Weather Station	Highest wind speed recorded (kph)	Av. of wind speed (kph)	Std. Dev. (kph)	Sample size
1. Grafton	38.9	30.4	6.04	19
2. Coffs Harbour	44.3	38.8	5.6	7
3. Williamtown	68	41.2	10.0	56
4. Sydney Airport	65	39.1	8.7	49
5. Nowra	55.4	37.4	9.8	43
6. Batemans Bay	83.2	53.4	20.9	7
7. Cooma	38.9	30.4	6.0	19
8. Canberra Airport	53.6	36.8	7.6	56
9. Goulburn	57.2	39.1	8.6	66
10. Bathurst	55.4	39.0	9.6	15
11. Armidale	N/A	N/A	N/A	0
12. Tamworth	50	35.8	8.14	30
13. Moree	68.4	37.7	14.4	34
14. Coonamble	68.4	33.0	12.4	59
15. Dubbo	55.4	31.2	8.3	69
16. Young	41	26.0	6.8	37
17. Wagga Wagga	51.8	30.8	7.4	163
18. Deniliquin	68.4	29.3	9.6	132
19. Hay	68.4	37.7	14.2	35
20. Mildura	55.4	28.6	9.8	291
21. Cobar	57	24.1	8.3	179

Note: Sample size refers to the number of days with an FFDI$\geq$50. 37.5 years of data.

From the results presented in Table 6.6 above, wind speeds for all sites where the fire weather conditions are rated as Severe or greater (i.e. FFDI$\geq$50) range from 24.1 to 53.4 kph. The site with the highest wind speed event is Batemans Bay (83.2 kph), which reflects its topographical and coastal location and may also account for the higher number of days recorded at FFDI$\geq$50 due to wind speed factors.

6.6.3Results of GEV assessment of wind speed

To further assess wind speed it is also appropriate to investigate the GEV values for wind speed (U_{10}). Two approaches were taken:

- Firstly, the GEV_{50} recurrence values for wind speeds can be assessed where the FFDI≥12 (filtered as with averages and percentiles in section 6.5.1).
- Secondly, the GEV_{50} recurrence values can be based on the rank of the wind speeds for the highest FFDI used to plot the GEV_{50} for FFDI in Table 6.3 above.

Wind is a key aspect of the DEFFM model, as well as grasslands and some shrubland models. Where used on its own, the role of GEV (or other *extreme* value) assessment can assist with determining the recurrence values for fire behaviour calculations. However, with both the FFDM5 and DEFFM, wind does not operate in isolation from other weather parameters such as temperature, relative humidity or rainfall.

This is discussed further in section 6.8 below.

Table 6.7 provides the results of both approaches for the 21 weather stations used within the current study.

Overall wind speeds in most weather districts are higher than the policy setting of 45 kph except for Young which is 44 kph based on both assessment approaches. When determining 10 minute wind speeds for use in forest fire calculations (DEFFM), Table 6.7 could be considered if the 50 year return period was warranted.

In general correlation coefficients are relatively large (i.e. greater than 0.7)with the exception of Grafton which gives the lowest r^2 value (0.48) for GEV_{50} wind speed for FFDI≥12 data.

Table 6.7: GEV_{50} wind speed (kph) where FFDI≥12 and for highest data used for determining GEV_{50} for FFDI with correlation coefficients

Fire Weather District No. /Weather Station	GEV_{50} Wind speed FFDI≥12 (kph)	r^2	GEV_{50} Wind speed (High FFDI) (kph)	r^2
1. Grafton	53	0.48	68	0.79
2. Coffs Harbour	57	0.96	53	0.88
3. Williamtown	70	0.95	72	0.89
4. Sydney Airport	74	0.97	70	0.96
5. Nowra	73	0.95	68	0.86
6. Batemans Bay	95	0.81	104	0.94
7. Cooma	60	0.95	52	0.80
8. Canberra Airport	59	0.95	61	0.91
9. Goulburn	68	0.88	68	0.93
10. Bathurst	61	0.96	72	0.81
11. Armidale	50	0.91	58	0.94
12. Tamworth	60	0.91	67	0.81
13. Moree	73	0.95	84	0.87
14 Coonamble	88	0.82	88	0.93
15. Dubbo	67	0.86	63	0.93
16. Young	44	0.78	44	0.91
17. Wagga Wagga	56	0.91	59	0.98
18. Deniliquin	69	0.73	67	0.91
19. Hay	73	0.95	84	0.87
20. Mildura	66	0.91	62	0.84
21. Cobar	56	0.95	61	0.93

Correlation coefficients for these sites is high with the exception of Grafton, which has a r2 value of 0.48 for the FFDI>12 filtered data. Interestingly, the wind speed for Grafton is lower for the larger dataset, whereas for high value FFDI analysis, the wind speed is greater. In many case the wind speed results between the two approaches give relatively close values.

6.6.4Wind direction

The study of winds associated with SEVERE and EXTREME fire events by Long (2006) for the state of Victoria showed a strong association with westerly to northerly wind direction (see Chapter 4). The number and the percentage frequency distribution analyses of wind direction were undertaken for the 21 NSW weather station sites and a wind rose was developed for each site. Examples of the percentage distribution of wind directions and associated wind plot at Sydney and NSW are shown in Figure 6.10 and Figure 6.11.

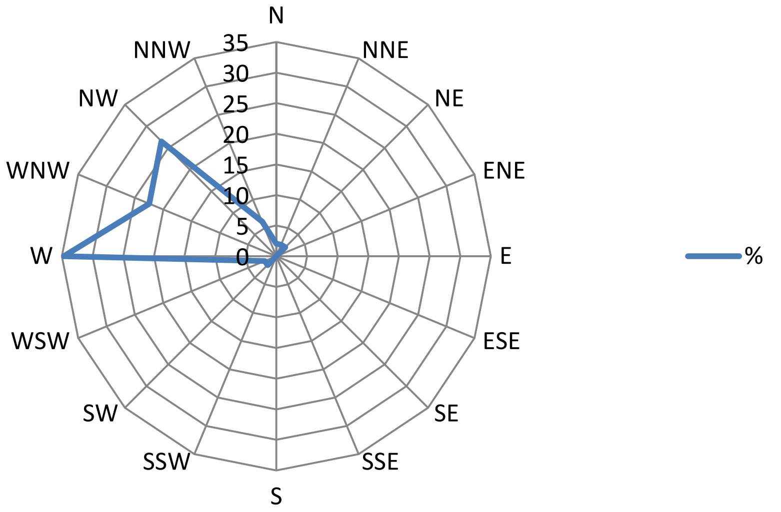


Figure 6.10: Percentage frequency distribution of wind direction under the condition of FFDI≥50 for Sydney (Airport) weather station for the period 1972-2009

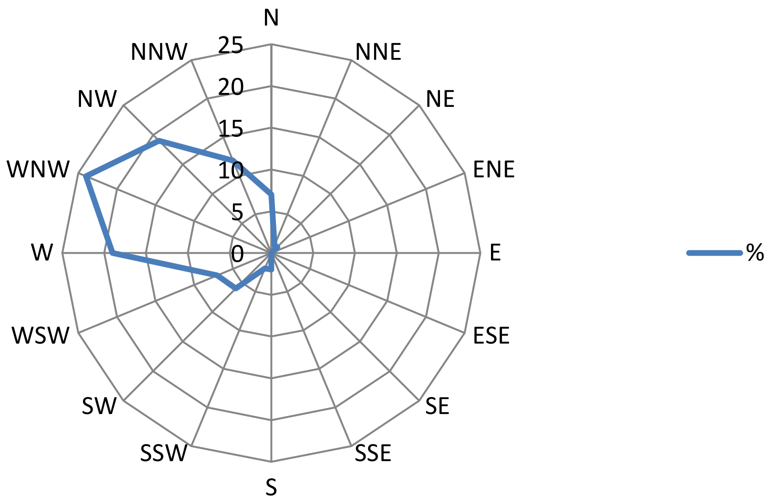


Figure 6.11: Averaged percentage frequency distribution of wind direction under the condition of FFDI>50 for 21 NSW weather stations for the period 1972-2009

Table 6.8 provides the number distribution for prevailing wind direction associated with FFDIs$\geq$50 for each of the 21 NSW weather stations used in the current study and the overall (averaged) percentage frequency distribution of wind direction for the entire state. Such an assessment provides an approximate conditional probability distribution, or in other words, a snapshot of wind conditions in terms of prevailing conditions when fire weather is SEVERE to EXTREME, for developing the wind direction parameter of a design bushfire.

Table 6.8: Number and frequency distribution of wind directions for FFDI>50 for 21 Fire Weather Districts

Fire Weather District	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	No.
1.	0	0	0	0	0	0	0	0	1	1	1	2	4	6	3	1	19
2.	0	0	0	0	0	0	0	0	0	0	1	1	3	2	0	0	7
3.	0	0	0	1	0	0	0	0	0	0	0	0	6	32	13	2	54
4.	1	1	1	0	0	0	0	0	0	0	1	1	17	11	13	3	49
5.	0	0	0	0	0	0	0	0	0	0	1	2	12	18	9	0	42
6.	0	0	0	0	0	0	0	0	0	0	1	0	0	4	1	1	7
7.	0	0	0	0	0	0	0	0	1	1	2	1	3	5	3	3	19
8.	0	0	0	0	0	0	0	0	0	0	0	1	17	13	21	4	56
9.	0	0	0	0	0	0	0	0	1	0	0	2	21	30	8	4	66
10.	0	0	0	0	0	0	0	0	0	0	0	1	3	7	3	1	15
11.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12.	0	0	0	0	0	0	0	0	0	0	0	3	9	9	8	1	30
13.	4	1	0	0	0	0	1	0	0	1	3	9	5	2	7	7	35
14.	3	0	0	1	0	2	1	2	2	5	2	8	4	12	7	10	59
15.	4	0	0	0	0	0	0	0	1	3	11	3	16	11	12	7	69
16.	1	1	0	0	0	0	0	0	1	2	4	4	7	3	8	6	37
17.	2	0	0	1	0	0	0	0	0	2	11	0	43	64	31	7	161
18.	12	4	0	0	1	0	0	0	2	4	15	16	10	20	24	23	131
19.	4	1	2	0	0	0	1	0	0	0	3	9	5	2	7	1	35
20.	56	8	6	1	0	0	0	2	6	3	4	9	39	34	61	62	291
21.	12	2	2	0	1	0	0	3	9	6	16	23	29	36	26	14	179
No.	99	18	11	4	2	2	3	7	24	28	76	95	253	321	265	157	1361
%	7	1	1	0	0	0	0	0	2	2	6	7	19	24	19	12	100

The wind rose results for other weather stations used in the study can be found in Appendix 8. Appendix 9 provides the wind speed and dominant wind direction results for all stations used in the current study. There were no 3:00 pm CALM days recorded at FFDI 50 or greater.

Figure 6.10 and Table 6.8 shows that for all weather stations, the dominant wind direction associated with SEVERE and EXTREME fire weather conditions are from the northerly to the westerly direction in NSW. This is consistent with the findings of Long (2006) in Victoria (see also Chapter 4).

6.6.5Discussion

The current policy setting under AS3959 and NSW planning requirements for wind speed used in fire behaviour modelling uses wind speeds of 45kph. Averages of wind speeds generally fall below the threshold value of 45kph used for grasslands (see Chapter 4). However, the maximum mean wind speed values generally fall close to or exceed 45kph. The 50 year recurrence values of filtered wind speeds all exceed the policy setting of 45 kph with the sole exception of Young, which is 44 kph and approximates the 45kph value.

As can be seen, the choice of FFDI values of 50 or greater as the basis for determining mean wind speed is limiting, especially where there are few FFDI 50 or greater values in the data. This is most obvious in the Armidale (New England) where there a no recorded values of greater than 50 and the 50 year recurrence value for Armidale is 46 (see Table 6.3).

The use of GEV_{50} to determine mean wind speed conditions shows that the resultant values are significantly higher than those of average values where FFDI$\geq$50 (Table 6.4).

When using GEV approaches, both the plotting of mean wind speeds of FFDI values, as well as high mean wind speeds where FFDI>12, yield more useful results than either average values of FFDI>50 or maximum wind speed. The GEV assessment of wind speed for values exceeding FFDI of 12 would provide a better fit of the data and correlation when plotted for mean wind speeds. However, it cannot be said from the data, that both approaches provide for a higher or lower value overall.

As the DEFFM fire behaviour equations are independent of maximum FFDI values, the use of the more general FFDI $\geq$12 values provide a more realistic result when considering mean wind speeds as a factor in calculating fire behaviour.

The assessment of wind speeds (Table 6.8), indicates that for wind conditions where the FFDI $\geq$50, then the predominant wind directions are from the west through to the north-west.

6.7 Drought

Since drought is a medium or long term weather phenomenon in comparison to daily weather parameters such as temperature, humidity and wind, there are two major components to be considered.

Firstly, whether the global effects arising from SOI (and possibly IOD) could give rise to a trend in drought that is not apparent from climate change. In other words, will a trend in SOI better explain increases in historical FFDI rather than as has been suggested with GCM modelling?

The second issue arises from consideration of the trend in seasonal drought (notably summer and spring) by measuring changes on KBDI as an indicator of drought. It should be possible to determine whether like FFDI, KBDI performs well under an EVA analysis.

These issues are more fully explored in Chapter 8, however in this Chapter, it is possible to provide some basic statistics and the GEV_{50}, for KBDI for the 21 weather stations used in the current study.

6.7.1 General statistics for drought

An assessment of KBDI and Drought Factor was undertaken using GEV_{50} recurrence (for KBDI), and basic statistics based on averages and standard deviations (SD)(filtered with FFDI$\geq$12),as well as minimum DF and maximum KBDI. As drought factor cannot exceed 10 (Section 2.3.1), a maximum value was not required as all datasets had values of DF at 10. For KBDI, the relationship between 95% (with filtered FFDI$\geq$12) and maximum values was worth noting that all datasets had KBDI values of less than 100 mm within the FFDI$\geq$12 range.

Table 6.9: GEV_{50} recurrence and Statistics for KBDI and DF where FFDI≥12

Fire Weather Station	KBDI GEV_{50}	Drought Factor (DF)				KBDI (mm)			
		95%	Mean	S.D.	Min	95%	Mean	S.D.	Max
1. Grafton	181.3	10	9.3	1.0	3.8	166	118	34.6	178
2. Coffs Harbour	176.8	10	8.7	1.1	2.8	155	98	36.1	172
3. Williamtown	181.7	10	8.2	1.3	1.7	160	81	44.1	180
4. Sydney Airport	174.0	10	8.3	1.3	2.2	149	78	40.1	171
5. Nowra	192.4	10	8.4	1.3	2.5	162	**87**	42.0	185
6. Batemans Bay	166.1	10	8.0	1.4	3.5	140	64	40.0	162
7. Cooma	123.8	9.6	7.7	1.3	2.7	109	54	31.4	121
8. Canberra Airport	159.7	9.9	8.1	1.2	3.1	137	69	36.8	158
9. Goulburn	146.7	9.9	8.2	1.3	2.9	125	67	34.2	144
10. Bathurst	138.4	9.9	8.1	1.3	3.3	121	65	31.6	134
11. Armidale	108.9	9.0	7.4	1.1	4.1	75	42	20.4	96
12. Tamworth	179.1	10	8.9	1.1	3.3	156	96	38.0	173
13. Moree	188.4	10	9.3	0.9	4.6	166	115	37.3	186
14 Coonamble	192.7	10	9.1	1.0	3.4	169	108	38.8	185
15. Dubbo	197.6	10	8.8	1.1	2.3	163	98	41.6	192
16. Young	185.6	10	8.9	1.2	3.5	163	97	42.2	184
17. Wagga Wagga	179.9	10	8.8	1.2	3.4	163	99	42.5	178
18. Deniliquin	184.5	10	9.3	1.0	4.1	161	110	35.3	180
19. Hay	187.8	10	9.3	1.0	4.6	166	115	37.3	186
20. Mildura	192.8	10	9.5	0.8	3.8	170	125	36.1	192
21. Cobar	195.2	10	9.2	1.0	3.0	178	117	41.5	192

6.7.2 Results

For all sites, the 95% of drought factor (DF) equals or approaches 10 which is also the maximum value possible. This is largely confirmed by the maximum values of KBDI which are also high. The minimum values of Drought Factor (DF fall largely between 2 and 4 which are associated with higher rainfall events. The clear difference between maximum KBDI and mean or 95% gives some comfort that FFDI>12 is an appropriate filter for KBDI when considering GEV assessments. Drier inland areas have higher overall DF values, with Deniliquin and Moree having minimum DF values of 4.6. For all sites, the GEV_{50} for KBDI was higher than both the 95% filtered data as well as for maximum recorded values.

The lowest of the maximum and GEV_{50}KBDI values was the Armidale station(New England) associated with a DF of 9 (@95%), which also had the lowest GEV_{50} for FFDI and had no recorded FFDI of 50 or above. Armidale also had one of the second highest values for Minimum DF when filtered at 95%, associated with low numbers of drought days in the record. The shape parameters and intercepts for GEV50 KBDI can be found in Appendix 11.

The next lowest value of KBDI was associated with Cooma which had much higher minimum, mean and maximum values than Armidale. It is clear that all fire weather districts have potentially serious fire weather problems associated with drought. Mean drought factors also generally exceeded 8, and mean KBDIs exceeded 50 (except for Armidale).

6.8 Temperature and Relative Humidity

Temperature and relative humidity are ambient drivers of FFDI. Temperature and humidity usually follow an inverse pattern. Lower humidity is usually associated with higher temperature in SE Australia (Luke and McArthur, 1977). When considering temperature and humidity, it is important to identify the relationship of temperature torelative humidity during HIGH fire danger rating periods when fires may be difficult to control (i.e. when FFDI$\geq$12).

Data is available for all weather stations on daily maximum temperature, however, for some days within the dataset, relative humidity data may be absent from some stations. The missing FFDI values are most likely associated with the absence of relative humidity data and/or wind speed. As such, care should be taken in considering any assessment of relative humidity, as the absence of data may bias any results. Any gaps during the winter period are unlikely to exceed FFDI 12. In summer and spring, on average, FFDI will also not exceed 12 as shown in Table 6.1. Gap filling was necessary to minimise bias and was based on other weather station data and days prior to and after for relative humidity values.

Gap filling is important as FMC is a function of temperature and humidity (see section 2.6 and Eqs 2.23 and 2.24).

6.8.1 Statistics for Tmax and RH

Table 6.10 provides an assessment of weather stations within NSW Fire Weather Areas of maximum daily temperatures (Tmax) and 3:00pm relative humidity (RH) for the data where FFDI≥12. This assessment includes sample size (N), 95 percentile (95%) values of Tmax and 5 percentile (5%) values for RH, average values with standard deviations (SD), minimum and maximum values.

Table 6.10: Statistics for maximum temperature (Tmax) and relative humidity (RH) at 3:00 pm, where FFDI>12(1972-2009)

District and Weather Station	Sample size*	Tmax				RH			
	N	95%	Mean	S.D.	Range	5%	Mean	S.D.	Range
1. Grafton	612	36	28	5.0	16 - 44	20	28.3	5.6	44 - 15
2. Coffs Harbour	359	37	25	5.8	15 - 43	14	28.5	10.7	62 - 6
3. Williamtown	1490	39	29	6.3	13 - 44	14	29.2	9.6	55 - 5
4. Sydney Airport	1302	38	27	6.2	13 - 45	13	29.0	10.5	60 - 4
5. Nowra	1140	39	28	6.4	11 - 44	13	27.7	9.1	61 - 5
6. Batemans Bay	294	34	24	5.0	14 - 45	15	26.4	8.7	57 - 7
7. Cooma	1278	34	25	5.7	8 - 39	8	20.3	7.8	53 - 1
8. Canberra	2315	36	29	4.9	13 - 41	12	23.2	7.0	50 - 4
9. Goulburn	1298	35	26	5.6	9 - 40	11	23.0	8.1	50 - 2
10. Bathurst	1110	35	27	5.4	8 - 41	11	22.9	7.4	47 - 3
11. Armidale	223	34	27	4.9	11 - 36	13	22.5	6.2	37 - 9
12. Tamworth	2035	38	29	5.4	12 - 42	13	25.0	7.5	53 - 5
13. Moree	3648	41	32	5.4	12 - 46	12	22.8	6.7	62 - 3
14 Coonamble	2370	39	31	5.8	14 - 45	12	24.2	7.4	56 - 1
15. Dubbo	3732	39	31	5.2	12 - 45	12	24.5	7.3	51 - 5
16. Young	1861	38	29	5.2	14 - 43	11	22.5	7.4	47 - 3
17. Wagga Wagga	3877	39	31	5.1	13 - 45	10	21.9	7.4	54 - 2
18. Deniliquin	2303	39	29	6.0	12 - 47	9	22.6	8.2	49 - 2
19. Hay	3648	41	32	5.4	12 - 46	12	22.8	6.7	62 - 3
20. Mildura	6236	39	29	5.9	14 - 47	10	22.9	7.8	77 - 0
21. Cobar	6025	40	31	5.7	12 - 47	9	20.2	7.3	49 - 0

* Sample size is number of days of FFDI≥12.
Range relates to minimum or maximum values associated with FFDI>12.

The sample size (i.e. the number of days) is affected by both geographical location and the number of years of available data, with sample sizes of in excess of 1,000 being associated with 37.5 years of data, and those less than 1,000 being associated with 16 years of data.

6.8.2 Discussion of Tmax and RH

The 95% values for maximum daily temperature ranged from 34-41°C, with highest maximum temperatures ranging from 36-47^{o} C. Average maximum temperatures associated with FFDI$\geq$12 were found within the 24 - 32^{0} Celsius range, with western inland areas having higher temperatures than coastal areas or elevated areas (New England and Monaro-Alpine).

For relative humidity, the relationship is similar, although minimal relative humidity, rather maximum relative humidity is important for determining fire weather conditions.

Relative humidity for 5 percentile values ranged from 9-20% with the highest being associated with the Far North Coast (e.g., Grafton) and lowest values associated with the Southern Riverina (e.g., Deniliquin) and Far Western areas (e.g., Cobar). The areas of Far Western NSW were generally lower at 5 percentile values than the coastal areas. The Coastal areas from North Coast, Hunter, Greater Sydney Illawarra/South Coast and Far South Coast all had 5 percentile values of 13-15%, while minimum values ranged from 4-7% RH. The central western districts of Central Ranges (Bathurst), Southern Ranges (Goulburn), ACT (Canberra) and North-western fire weather areas all have 5 percentile values of 11% RH, with minimums ranging from 2-5% RH.

6.8.3 GEV_{50} assessment of maximum temperature and relative humidity

From the literature (Dury, 1972 and Coles, 2004), daily maximum temperature and 3:00pm relative humidity follows an *extreme* value distribution [Eq. (5.1)] and the GEV techniques can be applied. A GEV assessment was undertaken for temperature and relative humidity for each of the 21 sites used in the study. Neither Gumbel nor GPD assessments were undertaken as the GEV approach has been determined as most appropriate in section 6.3 and 6.4 above. It should be noted that the use of *extreme* value assessments is not required for Tmax or RH, as these are not directly required by either FFDM5 or DEFFM flame height equations. As such, the GEV_{50} assessment was only undertaken for illustrative purposes.

6.8.4 Results of GEV_{50} assessment

Daily maximum temperatures (Tmax) and 3:00pm relative humidity (RH) data were filtered using FFDI>12, as with wind speed for consistency of approach. This was designated Tmax(T). However, it was readily observed that the highest ranked Tmax and minimal RH corresponded well with FFDI>25 over all weather stations, and FFDI > 50 for most. For comparison, maximum temperatures and minimum RH were also subjected to GEV_{50} analysis for the top ranked (highest) FFDI values as the filter and is designation Tmax(FDI). Likewise for RH, the GEV_{50} assessment was undertaken using the FFDI>12 filter and is designated Rh(RH), whereas the curve using the top ranked FFDI values for the FFDI GEV_{50} was designated RH(FDI). Examples of the resultant GEV graphs are shown in Figures 6.12 and 6.13.

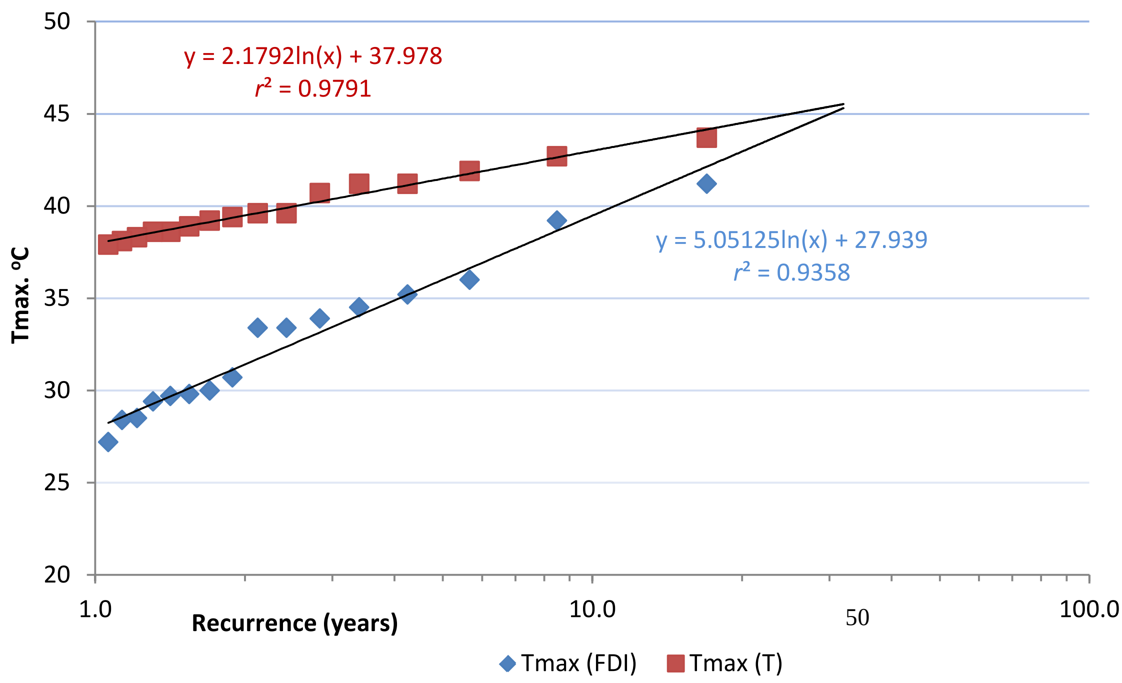


Figure 6.12: GEV assessment for filtered Tmax(T) and for ranked Tmax(FDI) values for Grafton. Best-fit curves and correlation coefficient (r^2) shown

As can be seem in the graphs, both curves follow the GEV distribution used for FFDI with a high correlation coefficient (r^2).

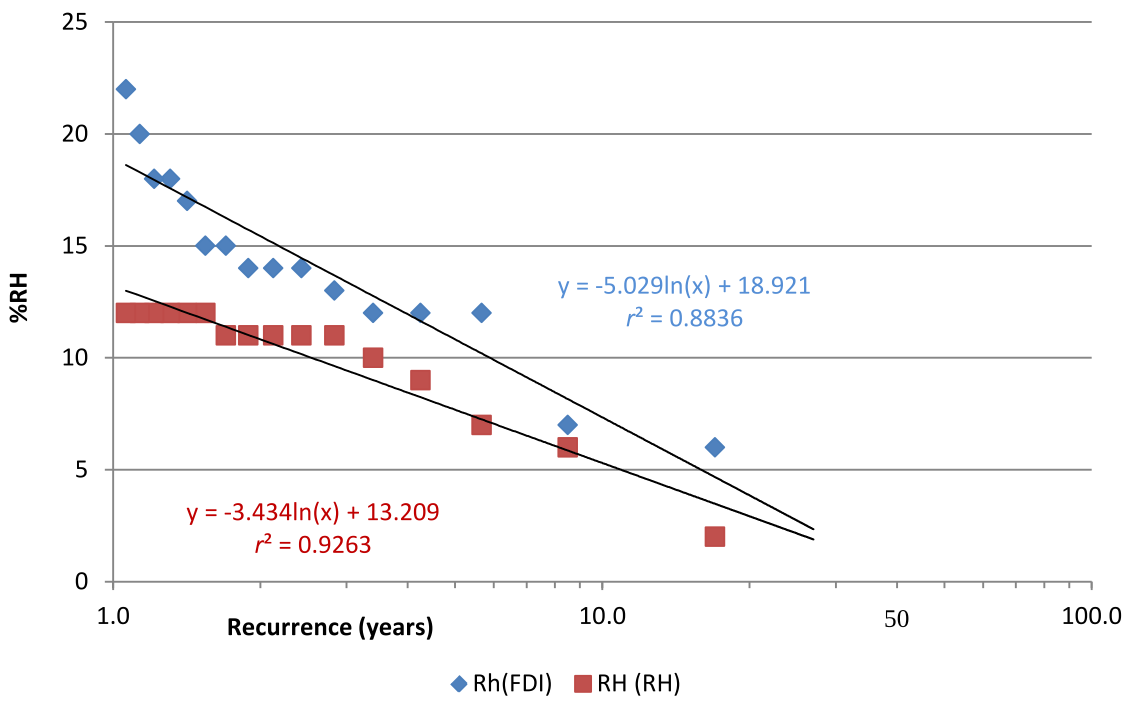


Figure 6.13: GEV assessment for filtered relative humidity only Rh(RH) and for the RH(FDI) values for Grafton

6.8.5 Discussion of GEV_{50} assessment

The GEV distribution for filtered Tmax values [(Tmax(T)] in Figure 6.11 is, as expected, higher than that of Tmax values associated with the GEV for ranked FFDIs [Tmax(FDI)]. For Grafton, a 1:20 year return period corresponds to 44.5°C for both curves, with the FFDI maximum temperature curve increasing over the maximum temperature curve exceeding that the 1:20 years return value. This also corresponds roughly to the observed maximum value. Although it would be possible to do a more intense GEV assessment for daily maximum temperature, using the 50 year dataset provided by the BoM, this could not provide a comparable dataset for FFDI maximum temperature values. As such, the GEV_{50} daily maximum temperature analysis was applied to the current datasets in order to be comparable with the FFDI recurrence analysis.

As with the temperature curve, the GEV distribution for relative humidity shows that the associated GEV_{50} values are lower than those of relative humidity alone, with the curves intersecting at a 1:35 year return period (at 1% RH). However, there is a limit of 0% for RH, which is achieved at about a 1:44 year return period (for Grafton). Although a 2%

limit has been established further inland, a 2% RH is less likely closer to the coast (see section 2.6).

Relative humidity and maximum temperature were assessed using two data filtering approaches. The first filtered data on the basis of FFDI>12 (High Fire Danger Rating). The second relied solely on the temperatures or relative humidity associated with the data points used for deriving the GEV FFDI assessment. Although the curves for each approach are at some variance with each other, the area within the range of 1:20 to 1:50 return periods yield similar outcomes for both curves at each weather station (i.e. within 1 or two degrees Celsius).

Temperature and humidity have practical limits and are used in deriving FFDI and FMC, rather than being used directly into fire behaviour calculations (Sections 2.2 and 2.3).

6.9 Case Study of GEV_{50} FMC and Wind speed

As discussed previously, the use of GEV assessments for wind speed and for Tmax and %RH as part of the development of a design bushfire can present problems. This arises when considering the combined effect of the product of wind speed probability, with that of fuel moisture probability, potentially inflating the risk values associated with the design bushfire.

The case study provides a comparative assessment of the relative impacts on the GEV assessment, based on input, intermediary and outputs from the two forest bushfire behaviour models (FFDM5 and DEFFM).

So as to compare the two forest fire behavior models it was necessary to investigate the inputs fuel loads for the FFDM5 model, and fuel structure expressed as hazard scores and/or ratings with wind speed for DEFFM model (see Chapter 3).

In addition, the two models require different fire weather inputs (see Chapter 2). The FFDM5 model relies on the forest fire danger index (FFDI) as an interim parameter to incorporate a set of weather data including wind speed as explained in Eq. 2.5, whereas the DEFFM model uses the fuel moisture function as an interim parameter and wind speed as an explicit input parameter (Eq. 2.10).

The outputs of the two models are rates of spread and flame heights, which are provided by both models.

6.9.1 Scenario development

In order to compare the two bushfire behavior models for evaluating design bushfire conditions, four scenarios were selected from two neighbouring NSW weather stations (Coffs Harbour and Williamtown) using three vegetation classes (North Coast WSF, North Coast DSF and Hunter-Manning DSF) that are found in those areas (Table 6.11). These four scenarios were used to consider whether further investigation of the impacts of multiple weather parameters was warranted. Table 6.11includesfuel load (*W/w*), fuel hazard scores (*FHS*) and fuel height (*H*)information.

Scenarios 1 and 2 share the same weather conditions but have two different vegetation classes (i.e. North Coast WSF and North Coast DSF). Likewise, Scenarios 3 and 4 share the same weather conditions which differ from Scenarios 1 and 2, and use one of the same and one different vegetation class (North Coast WSF and Hunter Manning DSF) found in scenarios 1 and 2.

As has been considered previously, bushfires are more readily controlled when the FFDI falls below 12 (RFS, 2002), the criteria of FFDI$\geq$12 is applied to the weather data to filter out non-fire weather conditions before they are subjected to GEV analysis and other statistical analysis.

Table 6.11: Location and vegetation characteristics for the four study scenarios

Scenario number	**1**	**2**	**3**	**4**
Weather Station	Coffs Harbour	Coffs Harbour	Williamtown	Williamtown
Vegetation classes	North Coast WSF*	North Coast DSF#	North Coast WSF*	Hunter Manning DSF#
w (tonnes/Ha)	25.6	24.5	25.6	15.7
W (tonnes/Ha)	35.7	28.0	35.7	24.5
$FHS_{\text{surface fuel}}$	3.80	3.70	3.80	3.20
$FHS_{\text{near surface fuel}}$	3.40	3.70	3.40	3.20
$H_{\text{surface fuel}}$(cm)	33.2	38.6	33.2	29.0
$H_{elevated}$ (cm)	254	226	254	233

* WSF – wet sclerophyll forests; # DSF – dry sclerophyll forests.*FHS*= Fuel hazard score. *w*=non-canopy fuel load, *W*= total fuel load, *H*= Height of vegetation

6.9.2 Analysis and results

A challenge for any time series weather data is the treatment of parameters that have various degrees of interdependence. For example, temperature and relative humidity are largely dependent parameters. Wind speed, on the other hand, is more or less an independent parameter and does not have a direct relationship with temperature or humidity.

The application of GEV analysis to fire weather conditions may not be straightforward as the fire weather is influenced or determined by multiple weather parameters and the *extreme* fire event or fire event condition may not correspond to the *extreme* values of individual parameters. For example, wind speeds at the *extreme* are not necessarily associated with bushfire weather, but rather for cyclonic or other high wind conditions. Drought may be associated with winter as well as summer conditions where temperatures are moderate. Therefore, it would be necessary to examine the weather parameters collectively as well as individually when evaluating the *extreme* bushfire weather conditions.

Since the rate of spread *Rm* and flame height *Zm* estimates from the MacArthur model are linear functions of FFDI, the 1:50 recurrence values of the former two can be easily obtained from the corresponding recurrence value of the latter (section 2.3.1). The recurrence model for FFDI was obtained from the daily weather parameters, as in Eq. (2.1), directly. The 50 recurrence values of rate of spread and flame height were estimated from the 50 recurrence values of FFDI through Eqs. (2.4) and (2.6). The slope angle was set to zero in the estimate.

As for the DEFFM model, the rate of spread and flame height is a function of multiple variables. The following three methods are applied and the results are compared:

1. The daily conditions of *T* and *H* are directly supplied to Eqs. (2.22) then (2.23) and (2.24) to determine *FMC*. Then together with *U* and the *FMC* to Eqs. (2.9) and (2.10), the results of *Rv* and *Zv* are then subjected to GEV analysis.

2. Only the daily conditions of *T* and *H* are directly supplied to Eqs. (2.23) or (2.24) then (2.22). The interim result of *FMC* is subjected to GEV analysis. On the other hand, the average of $U_{10}$of the top *n*+1 values over the period of *n* years is evaluate, i.e.,

$$U_{ave} = \frac{1}{n+1}\sum_{m=1}^{n+1} U_m \qquad (6.1)$$

where U_m is the *m*th highest wind speed recorded in the *n* years' available data. The 1:50 year recurrence result of *FMC* and U_{ave} is used to estimate *Rv* in Eq. (2.9), then to estimate *Zv* in Eq. (2.10).

3. The wind speed *U* (where the FFDI>12) is subjected to GEV analysis separately. The 1:50 year recurrence results of *U* and *FMC* are supplied to Eqs. (2.9) and (2.10) to estimate *Rv* and *Zv*.

Methods 1 is an application of GEV to the output parameters of the model. Method 2 involves the application of GEV to the interim parameter only whilst the wind speed parameter is subjected to averaging. Methods 3 represents the applications of GEV to the interim parameter and the wind speed parameter separately.

Presented in Figure 6.14 are the results of GEV analysis of rate of spread and flame height from the DEFFM model based on Method 1. It is seen from this figure that the logarithmic regression of the GEV produces good fits to Scenarios 3 and 4 but relatively poor fits to Scenarios 1 and 2.

The 38 year plot point is proportionally larger than the remainder of the series data, for Scenario 1 and 2, which arises principally from the fuel moisture and wind speed conditions at this ranked position.

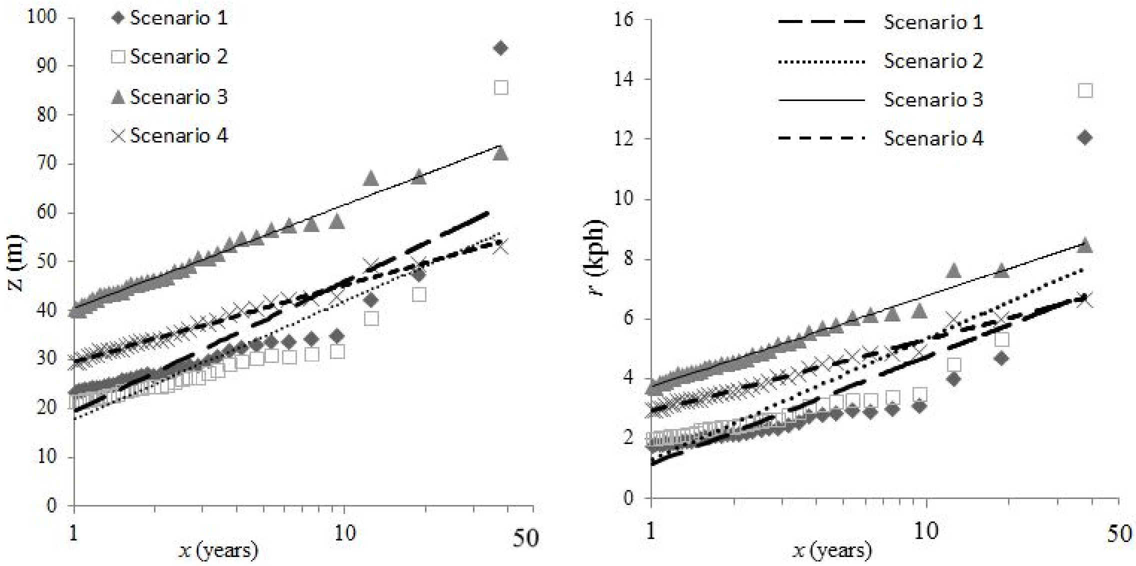


Figure 6.14: Flame heights and rates of spread for 4 test scenarios

As is seen in Figure 6.14, the variations in recurrence values of rate of spread and flame height are highly non-linear in the linear-log plots for Scenarios 1 and 2. Therefore, the use of the linear-log expression as a means describing the variation trend of recurrence values for these two particular scenarios would involve a degree of inaccuracy. This could be partially offset with additional years of data, which was not available at the time of this assessment.

The regression line fit parameters and the corresponding correlation coefficients are listed in Table 6.12.

Table 6.12: Line fit parameters and correlation coefficient

Scenario	***Rate of Spread***			***Flame Height***		
	α	β	r^2	α	β	r^2
1	1537	1179	0.618	11.37	19.68	0.697
2	1739	1333	0.618	10.39	17.97	0.697
3	1323	3719	0.987	9.21	40.41	0.988
4	1037	2920	0.987	6.75	29.65	0.988

Table 6.13 lists the derived fire weather parameters and fuel moisture as inputs for the two fire behaviour models. Note that *FMC* (1:50 year), $U_{average}$ and *U* (1:50 year)are derived according to Methods 2 and 3 as described in the foregoing.

Table 6.13: Fire weather parameters and fuel moisture derived for the two models

Model	**Parameter**	**Scenario**			
		1	2	3	4
FFDM5	*F* (1:50 year)	96	96	106	106
DEFFM	*FMC* (1:50 year) (%)	2	2	2	2
	$U_{average}$(kph)	39	39	41	41
	U (1:50 year)(kph)	57	57	70	70

Table 6.14 provides a comparative analysis of the fire behaviour parameters estimated from the two models. It can be observed that at the recurrence interval of 50 years, the rates of spread estimated from the DEFFM model (Method 1) are 140% to 250% greater than (or 2.4 to 3.5 times) that of the FFDM5 model for the four scenarios.

This difference is related to the intrinsic difference in the modelling approach as summarized in section 2.3 and is similar to that observed when the two models are applied to the same weather condition of a given day (McCaw et al, 2008).

Table 6.14: Estimated 50 year recurrence values of the output parameters of two bushfire behaviour models

Parameter*	**Scenario**			
	1	2	3	4
R_m (m/hr)	2950	2820	3260	2000
R_v (m/hr)	7192	8135	8896	6978
Z_m (m)	44.9	41.4	48.9	29.8
Z_v (m) (Method 1)	64.2	58.6	76.5	56.1
$Z_{v,Uaverage}$ (m) (Method 2)	109.4	100.0	114.1	80
$Z_{v,U-(1:50)}$ (m) (Method 3)	142.4	124.0	163.4	114.5

* Subscript *m* indicates the result from FFDM5 model and *v* the result from DEFFM model.

The difference in the estimated flame heights between the two models varies from 42% to 89%. From determining design bushfire point of view, this difference in the estimated flame heights may be acceptable being of the same order of magnitude. However, when using either Method 2 or Method 3, the resultant flame heights from the DEFFM model differ from that from the FFDM5 model by factors from 2.4 to almost 4. Therefore, Methods 2 and 3 provide exaggerated flame heights that are unsuitable for determining design bushfires.

6.9.3 Discussion and conclusion

The design bushfire conditions can be determined by statistical analysis of historical fire weather data and by applying bushfire behaviour models to estimate fire characteristics. In this case study, the GEV method has been applied to weather parameters, the interim parameters and the output parameters of two fire behaviour models. In particular, the parameters involved in the DEFFM model were treated using 3 different methods. It is found that the GEV analysis of the final output parameters of the DEFFM model (i.e., Method 1) produced best agreement with the MacArthur model in comparison with the other two methods (Methods 2 and 3).

The 50 year recurrence values of rate of spread predicted by DEFFM model for a number of typical regions in southeast Australia are 2 to 3.5 times that of MacArthur model, confirming previous assessment reported in the literature (McCaw et al, 2008) which identified that this difference is a crucial issue for operational considerations. The 1:50 year recurrence values of flame heights predicted by DEFFM model (Methods 1) are greater than that of MacArthur model for the four scenarios studied. When the average wind speed (Method 2) or 1:50 year recurrence of wind speed (Methods 3) were used as input, the DEFFM model significantly over-estimate flame height as compared to the results of Method 1 and of MacArthur model.

When the GEV method is applied for determining the design bushfire conditions, caution should be taken in selecting the input parameter values for bushfire behaviour models. The use of recurrence values of input parameters independently will result in excessive estimates (or overly conservative estimate from safety point of view) of design bushfire conditions as in the case of DEFFM model. From a practical point of view, the overestimate of flame height would lead to the requirement of more stringent fire protection measures and hence less cost-effective solutions. The application of GEV analysis to the output of fire behaviour models is more appropriate when considering different fire behaviour models, notably the DEFFM and shrubland models which are reliant on using multiple weather parameters (e.g. wind and FMC).

In the present study only four scenarios involving different combinations of vegetation classes and weather conditions in four regions in southeast Australia were investigated. It is not certain that the trend of DEFFM model being more conservative than FFDM5 model can be generalized to a much wider region. This will now be investigated in Chapter 7.

6.10 Summary

95% assessments where undertaken for FFDI, DF, KBDI, RH and Tmax using a filter of FFDI>12. In addition, mean values (with standard deviation) were also considered.

Three *extreme* value assessments were then applied to fire weather conditions and fuel moisture. FFDI, fuel moisture, wind speed, maximum temperature, relativity humidity and KBDI conditions can be best modelled with the theory of *extremes*. The use of extreme value assessments provides a robust tool for the determination of risk at the extreme. However, there are limitations and application of extreme value assessments should be applied at the design bushfire and not solely at fire weather conditions.

Overall, the generalised extreme value (GEV) assessment approach provides the best fit of data and best correlation coefficients for FFDI and %FMC. The classical Gumbel approach using calendar years is least effective for these parameters, however, previous work by Louis (2014) for seasonal years suggests that return periods of 1:50 years yield similar results for the Gumbel distribution compared to GEV or the GPD. There is a reasonable level of convergence between the current study and that of Louis (2014), however, no previous work on fuel moisture or KBDI at the *extremes* has been identified. Even where work has been considered for FFDI, the use of GEV has not been adequately explored.

In reviewing current policy settings for FFDI and FMC, it is desirable to consider both GEV and GPD results, although GEV provides the easiest method for determining return periods for FFDI, FMC and KBDI. Chapter 7 will explore the likely trends of FFDI, FMC and KBDI for planning and construction practice, focussing on the GEV_{50}.

The assessment of dominant wind directions confirms previous studies of Long (2006) and Mills (2009) in that the most likely winds associated with *extreme* bushfire conditions are from the north, north-west and west. There are a significant proportion of *extreme* fire weather events associated with the west-south-west to south-south-west direction, suggesting the influence of associated changes in wind direction observed in SE Australia, and associated with major house losses (Mills, 2009). Wind speeds for most sites exceed the policy setting of 45kph used in calculating fire behaviour for grasslands or heaths, and as applied within the DEFFM forest fire behaviour conditions.

Fuel moisture was also assessed for its 1:50 year return period. In some cases, the resultant fuel moisture content fell just below the critical 2% FMC, considered an absolute lower limit for open forests. Most values for the 1:50 year return period lie within the 2-3% range, with none exceeding 3.55%.

From the use of the case study, it can be seen that the advantages of the GEV model is that it can be applied to the outputs of the two forest fire behaviour models, that is, rates of spread and flame height, rather than either the inputs or the intermediary parameters. The challenges therefore arise when applying the log-linear GEV recurrence model to either intermediate or input parameters, when comparing different fire behaviour models. In the case of FFDI, there is a direct relationship between the intermediate parameter and the output, whereas for the DEFFM model, the outputs are dependent on the two intermediate parameters of FMC and wind speed.

CHAPTER 7- SYNTHESIS AND APPLICATION OF RESEARCH TO CONSTRUCTION PRACTICE.

7.1 Introduction

In this chapter, the intention is to provide for the synthesis of the outcomes arising from Chapter 6 and to consider the potential applications of the GEV approach for construction practice within the NSW fire weather districts.

In chapter 6, the recurrence periods were derived for fire weather characteristics in each of the 21 fire weather districts. These included:

- FFDI (1:50 year GEV, Gumbel and GPD),
- FMC (1:50 year GEV, Gumbel and GEV),
- KBDI (1:50 year GEV).

In addition, filtered percentile and average values were considered for 3:00 pm wind speed, 3:00 pm relative humidity and daily maximum temperature. In of themselves, these assessments do not provide assistance with design bushfire, as combined with GEV assessments for wind and/or fuel moisture content, highly conservative outcomes will be generated. The impact is considered within the case study in section 6.8.

In this Chapter, a synthesis of *extreme* value assessments will be made of the comparative fire behaviour characteristics (as described in Chapter 2) in terms of rates of spread and flame height between FFDM5 and DEFFM models.

To undertake this process, a set of representative vegetation classes with fuel load characteristics (for FFDM5 calculations), as well as fuel structure arrangements (which can be used for DEFFM calculations) have been developed. These were derived from the characteristics of NSW vegetation classes and are described in Chapters 3.

As it has been identified that the use of GEV is most preferred for determining recurrence or return periods, the subsequent analysis for fire behaviour and trend analysis is derived from the GEV methodology and approach.

7.2 Flame Heights and Rates of Spread

There exist a number of empirical and quasi-empirical models for quantifying bushfire behaviour under Australian ecological and climatic conditions (Sullivan, 2009). One of them, the FFDM5 model has been used for planning and protection purposes (Douglas and Tan, 2005) since 2001 (RFS, 2006). The more recent alternate model (DEFFM) developed in Project Vesta (Cheney et al, 2012) is believed to more accurately reflect rates of spread in higher intensity fires, however the fuel assessment and weather parameters differ in deriving rates of spread and flame length from that of FFDM5. A third model based on the *Forest Fire Behaviour Tables for Western Australia* (FFBT) and used only in Western Australia (see Cruz et al, 2015a) has not been considered in the current study.

7.2.1 Results

Table 7.1 and Table 7.2 below provide examples of the combined GEV analysis of rates of spread and flame heights for all vegetation classes identified in Chapter 5, within the respective 18 fire weather districts. These results provide a comparative assessment of rates of spread (Table 7.1) and flame heights (Table 7.2) for both FFDM5 and DEFFM models for flat terrain conditions (i.e. 0° slope).

These rates of spread and flame heights for DEFFM were derived directly from the daily calculated rate of spread and flame heights using equations 2.7 and 2.8 discussed in Chapter 2. This is necessary as the use of 1:50 return period values for fuel moisture (see Chapter 6) and wind speeds would give exaggerated (i.e. higher) rates of spread and flame lengths.

Because of the direct relationship between FFDI and rate of spread and flame height, the FFDM5 values were calculated on the GEV_{50} FFDI values, with appropriate fuel inputs from Table 7.2 above. The rate of spread calculations were given as kph and hence converted to m/hr for comparative purposes. This has meant that FFDM5 calculations are to the nearest 10 m/hr, whereas DEFFM calculations are to the nearest 1 m/hr.

Mean and standard deviation values have also been determined for both rates of spread and flame height as a form of overall State average of 1:50 year return periods.

Table 7.1: Comparative GEV_{50} year return period Rates of Spread (m/hr) between FFDM and DEFFM for flat ground (0^o slope)

Fire Weather District	Forest Vegetation Classes																	
	NC-WSF		NH-WSF		NC-DSF		Syd-DSF		SE-DSF		ST-DSF		HM-DSF		Cu-DSF		CVGW	
	FFDM5	DEFFM	FFDM5	DEFFM	FFDM5	DEFFM	FFDM5	DEFFM	FFDM5	DEFFM	FFDM5	DEFFM	FFDM5	DEFFM	FFDM5	DEFFM	FFDM5	DEFFM
1.FNC	3150	8689	2790	9130	2970	9831	2850	7810	2440	8309	2790	4586	1880	6816	1940	3612	1390	4593
2.NC	3000	7192	2650	7556	2820	8135	2710	6446	2320	6878	2650	3806	1840	5646	1790	3002	1320	3811
3.GHu	3310	8896	2930	9349	3120	10068	2990	7996	2560	8507	2930	4693	1970	6978	2040	3695	1460	4700
4.GSy	3060	9003	2700	9460	2880	10185	2760	8096	2360	8611	2700	4765	1820	7069	1880	3758	1350	4772
5.ISC	3490	8783	3090	9230	3290	9939	3160	7894	2700	8399	3090	4634	2080	6890	2150	3648	1550	4640
6.FSC	3030	7034	2680	7391	2850	7959	2740	6323	2340	6726	2680	3714	1800	5519	1860	2925	1340	3719
7.MA	2590	12124	2290	12739	2400	13716	2340	10900	2000	11594	2290	6409	1540	9516	1590	5053	1150	6419
8.ACT	3120	9253	2760	9722	2940	10467	2820	8485	2410	8319	2760	4891	1860	7262	1920	3856	1380	4899
9.SR	3280	10043	2900	10555	3090	11368	2960	9025	2530	9603	2900	5289	1950	7873	2020	4160	1450	5296
10.CR	2590	10033	2290	10544	2400	11354	2340	9017	2000	9594	2290	5291	1540	7869	1590	4165	1150	5298
11.NE	1440	5445	1270	5721	1350	6160	1300	4895	1110	5207	1270	2877	860	4273	880	2267	630	2881
12.NS	3120	9162	2760	9629	2940	10370	2820	8233	2410	8760	2760	4825	1860	7183	1920	3795	1380	4832
13.NW	3590	17644	3170	18544	3380	19971	3240	15855	2770	16871	3170	9291	2140	13832	2210	7308	1590	9304
14.UCW	3840	13735	3390	14434	3620	15545	3470	12343	2970	13133	3390	7237	2290	10770	2360	5695	1700	7248
15.LCW	3340	15651	2950	16448	3150	17712	3020	14066	2580	14966	2950	8251	1990	12274	2050	6494	1480	8263
16.SSl	2460	8010	2180	8416	2320	9060	2230	7203	1910	7661	2180	4242	1470	6290	1520	3347	1090	4248
17.ERi	3810	5314	3370	5584	3590	6013	3440	4777	2940	7661	3370	2807	2270	4242	2340	2212	1680	2811
18.SRi	4090	9586	3620	10072	3850	10844	3690	9619	3160	9168	3620	5072	2440	7526	2520	4000	1810	5080
Mean	3128	9755	2766	10251	2942	11038	2827	8832	2417	9442	2766	5149	1867	7657	1921	4055	1383	5156
Std Dev.	606	3235	536	3401	577	3663	547	2913	468	2950	536	1701	361	2530	375	1337	269	1704

Table 7.2: Comparative GEV_{50} values of Flame Heights (m) between FFDM and DEFFM for flat ground (0^o slope)

Fire Weather District	Forest Vegetation Classes																	
	NC-WSF		NH-WSF		NC-DSF		SyC-DSF		SE-DSF		ST-DSF		HM-DSF		Cu-DSF		CVGW	
	FFDM5	DEFFM	FFDM5	DEFFM	FFDM5	DEFFM	FFDM5	DEFFM	FFDM5	DEFFM	FFDM5	DEFFM	FFDM5	DEFFM	FFDM5	DEFFM	FFDM5	DEFFM
1.FNC	47.6	75.7	42.2	78.5	43.3	69.2	41.5	82.8	36.3	55.7	42.2	15.5	28.3	55.5	29.2	23.0	20.4	31.5
2.NC	45.6	64.2	40.4	66.8	41.4	58.6	39.7	70.2	34.8	47.2	40.4	18.3	28.0	47.1	27.1	19.6	19.5	26.9
3.GHu	49.6	76.5	44.0	79.2	45.2	69.9	43.3	83.6	37.9	56.2	44.0	18.4	29.5	56.1	30.5	23.2	21.3	31.8
4.GSy	46.4	77.4	41.1	80.2	42.2	70.8	40.4	84.7	35.4	47.9	41.1	18.7	27.6	56.8	28.5	23.6	19.9	32.3
5.ISC	52.1	75.4	46.1	78.1	47.5	68.9	45.5	82.4	39.8	55.4	46.1	18.2	31.0	55.3	32.0	22.9	22.4	31.3
6.FSC	46.0	63.9	40.7	66.2	41.8	58.4	40.0	69.9	35.1	47.0	40.7	15.4	27.3	46.9	28.2	19.4	19.7	26.6
7.MA	40.3	95.0	35.7	98.5	36.4	86.9	34.9	103.9	30.7	69.9	35.7	23.0	24.0	69.7	24.7	28.9	17.2	39.6
8.ACT	47.2	78.2	41.8	81.0	42.9	68.7	41.1	85.5	36.0	57.5	41.8	18.9	28.1	57.4	29.0	23.8	20.3	32.6
9.SR	49.2	82.9	43.6	85.9	44.9	75.8	43.0	90.6	37.6	60.9	43.6	20.0	29.3	60.8	30.2	25.1	21.2	34.4
10.CR	40.3	83.3	35.7	86.3	36.4	76.1	34.9	91.0	30.7	61.2	35.7	20.1	24.0	61.1	24.7	25.3	17.2	34.6
11.NE	25.3	53.5	22.4	55.6	22.3	49.0	21.3	84.0	19.1	39.4	22.4	12.9	15.0	39.3	15.5	37.7	10.6	22.3
12.NS	47.2	76.8	41.8	79.7	42.9	58.3	41.1	58.6	36.0	56.5	41.8	18.5	28.1	56.3	29.0	18.1	20.3	31.9
13.NW	53.3	124.6	47.2	129.2	48.7	113.9	46.6	136.3	40.7	91.6	47.2	30.0	31.7	91.3	32.7	23.3	23.0	51.7
14.UCW	56.3	105.3	50.1	109.1	51.7	96.3	49.6	115.1	43.2	77.4	50.1	25.4	33.6	77.2	34.7	32.1	24.4	43.8
15.LCW	50.0	116.1	44.3	120.4	45.6	106.2	43.7	127.0	38.2	85.4	44.3	28.0	29.8	85.1	30.7	35.2	21.5	48.2
16.SSl	38.7	70.4	34.3	73.0	34.9	64.3	33.4	77.0	29.4	51.8	34.3	12.6	23.0	51.8	23.7	21.5	16.5	29.4
17.ERi	56.1	51.9	49.7	54.0	51.4	47.6	49.2	57.0	42.9	38.3	49.7	17.0	33.4	38.2	34.5	15.9	24.2	21.7
18.SRi	59.8	80.7	52.9	83.6	54.8	73.7	52.5	88.2	45.7	59.3	52.9	19.5	35.6	59.2	36.7	24.6	25.8	33.6
Mean	47.3	80.7	41.9	83.6	43.0	73.7	41.2	88.2	36.1	59.3	41.9	19.5	28.2	59.2	29.0	24.6	20.3	33.6
Std Dev.	7.9	19.3	7.0	20.0	7.4	18.0	7.1	21.1	6.1	14.4	7.0	4.6	4.7	14.1	4.9	5.7	3.5	8.0

The correlation coefficients for Tables 7.1 and 7.2 can be found in Appendix 12. This shows that the correlations are very high and comparable to those of FFDI.

7.2.2 Discussion

Districts 1-11 were considered to have some WSF vegetation, with districts 12-18 considered to be absent of WSFs (Chapter 3). DSF were more likely to occur in most districts, with the GWs being present across all districts, although two (Monaro-Alpine and New England) were substituted with the Cumberland DSF as these fuel loads were considered to be more realistic.

The results shown in Table 7.1 confirm the previously reported observation (McCaw et al, 2008) that rates of spread have been under-estimated for the FFDM5 model compared to that of DEFFM. It has been identified that rates of spread at the *extreme* of 1:50 year recurrence are more than three times greater under DEFFM predictions compared to those of FFDM5 predictions.

Of interest to note, is that the North-coast DSF rates of spread using DEFFM are faster than the North-Coast and Northern Hinterland WSF rates of spread. This arises from the hazard scores for the near surface and surface fuel components used in the DEFFM. This is of interest as the respective fuel loads would suggest that the WSF forests should have faster rates of spread than the DSF based on the traditional FFDM5 approach. As such, the use of suitable models is an important consideration when determining the design bushfire.

In some districts, the 50 year recurrence rates of spread may exceed 10 kph under DEFFM (up to 20 kph in some cases), whereas using the FFDM model, the same parameter rarely exceed 3 kph. The only exception to this was found in the more western districts due to the absence of WSFs, and where DEFFM rates of spread may be four times that of the FFDM5.

Conversely, flame heights for WSFs were larger than all DSF and GW classes for the DEFFM. Again, when examining the DEFFM, the elevated fuel height component for the WSF is larger than that of the DSF, hence the WSFs have larger flame heights, even when considering rates of spread. Using the FFDM5, the NC-DSF had a slightly higher flame height than the NH-WSF, largely associated with rates of spread rather than fuel loads.

For flame heights there was no consistent ‘rule of thumb’ that could be seen in the comparative results. Generally, flame heights were larger using DEFFM than using the FFDM5. The exceptions were for Cumberland DSF and Southern Tablelands DSFs, where, FFDM5 calculations gave higher flame heights than DEFFM. Again, this arises from the lower elevated fuel heights used in the DEFFM associated with this vegetation class. Where DEFFM flame heights were greater, then they are less than twice that of the FFDM5 flame heights.

For the purposes of determining BAL levels, the flame heights above are divided by two (see Chapter 2) and described as 'sustained flame heights', which adjusts the flame conditions to account for flame angle and flame discontinuities and flashes. These sustained flame heights can then be used for radiant heat modelling through the view factor method. This is considered in the next section.

7.3 Radiant Heat flux and Separation Distances Determination for Land-use Planning

In this section, the role of flame heights is considered within the context of deriving revised separation distances based on radiant heat modelling. Land-use planning and construction practice in Australia has largely relied on the FFDM5 model for forest and woodland vegetation class fuel loads in determining separation distances and is used with AS 3959-2009.

The bushfire attack level of 29kW/m^2 (or BAL 29) has been accepted as a suitable basis for the planning of future developments in NSW (subdivision and housing construction) and is discussed in Chapter 1. The distances (in metres) to the vegetation based on the exceedance of 29kW/m^2 are described as the 'critical distance'. Radiant heat levels are calculated using the 'sustained flame height'. As discussed previously, the sustained flame height is half the calculated flame height determined in Table 7.2 above (Douglas and Tan, 2002).

7.3.1 Planning distances for defendable space (APZs)

AS 3959-2009 prescribes the setback distances to be used for achieving key BAL levels for construction practice. In NSW, the current *Planning for Bush Fire Protection* document (RFS, 2006) also provides a range of distances, which were developed to achieve a maximum or critical radiant heat flux of 29kW/m^2. Table 7.3 below provides the stated FFDI, AS 3959 (2009) and PBP (2006) distances for each of the 18 fire weather districts (districts) with forested vegetation at BAL-29. It was assumed that these correspond to a 50 year recurrence (RFS, 2006).

The differences in fuel loads between PBP (RFS, 2006) and AS 3959-2009, arises from preliminary data assessment in NSW prior to the fuel modelling project by Watson et al (2012) and described in Chapter 3.

Table 7.3: Comparison of setback distances (m) for BAL 29 for 18 NSW fire weather districts under standard conditions (as at January 2016)

Fire Weather District (abbreviation)	FFDI	BAL 29 distance (flat ground)			
	AS 3959 (2009) PBP (2006)	PBP (2006)		AS3959 (2009)	
		Forest	Grassy Woodland	Forest	Grassy Woodland
1.FNC	80	20	10	21	14
2.NC	80	20	10	21	14
3.GHu	100	20	10	25	16
4.GSy	100	20	10	25	16
5.ISC	100	20	10	25	16
6.FSC	100	20	10	25	16
7.MA	80	20	10	21	14
8.ACT	100	20	10	25	16
9.SR	100	20	10	25	16
10.CR	80	20	10	21	14
11.NE	80	20	10	21	14
12.NS	80	20	10	21	14
13.NW	80	20	10	21	14
14.UCW	80	20	10	21	14
15.LCW	80	20	10	21	14
16.SSl	80	20	10	21	14
17.ERi	80	20	10	21	14
18.SRi	80	20	10	21	14

Standard conditions

(PBP, 2006): flat ground and 1090K flame temperatures, forest fuel loads of 20/25 tonnes per hectare for forests and 10/15 tonnes per hectare tonnes per hectare for grassy woodlands.

AS 3959 (2009): flat ground and 1090K flame temperatures, fuel loads of 25/35 tonnes per hectare for forests and 15/25 tonnes per hectare for grassy woodlands.

Flame dimensions calculated using MacArthur FFDI Mark 5 meter equations (Noble, et al, 1980). Emissivity of the flames is given as 0.95.

From Table 7.3, it can be seen that some differences arise from the difference in fuel loads used in determining setback distances on flat ground.

Table 7.4 provides the calculated distances (to BAL-29) using the data from the Fuel Modelling Project (Watson, 2011; Watson et al, 2012; UoW, 2013; Horsey and Watson, 2012) of the 9 vegetation classes and 18 fire weather districts considered in the current study. These distances have been calculated for the same conditions for flame temperature and flat terrain as per Table 7.3 above but with specific fuel loads (FFDM5) or fuel structure (DEFFM) for the determination of distances for radiant heat flux exposures using the GEV methodology.

The 8 vegetation classes identified in Table 7.4 have been used as an example for other NSW vegetation classes. These example vegetation classes are used where fuel characteristics are sufficiently similar to give likely similar outcomes, based on the limited information available. BAL29 distance is the whole number distance from the potential fire front, at or beyond which the radiant heat flux from the fire is no more than 29 kW/m^2.

Again, mean and standard deviation of each vegetation class across all the weather districts are provided for comparative purposes.

Table 7.4: Comparative 50 year recurrence critical distances (m) not exceeding 29kW/m^2 for FFDM5 and DEFFM for 18 fire weather districts and 9 vegetation classes (on flat ground (0^o)

Fire Weather District	GEV$_{50}$ BAL -29 distances for NSW Vegetation Classes (after Keith, 2004)																	
	NC-WSF		NH-WSF		NC-DSF		SyC-DSF		SE-DSF		ST-DSF		HM-DSF		Cu-DSF		CV-GW	
	FFD M5	DEF FM	FFD M5	DEF FM	FFD M5	DEF FM	FFD M5	DEF FM	FFD M5	DEF FM	FFD M5	DEF FM	FFD M5	DEF FM	FFD M5	DEF FM	FFD M5	DEF FM
1.FNC	26	38	24	40	25	36	25	41	21	29	24	9	17	30	18	14	13	18
2.NC	26	33	22	35	24	31	24	36	20	25	23	11	17	26	17	12	13	16
3.GHu	27	39	25	40	26	36	26	42	22	29	25	11	18	30	18	14	14	18
4.GSy	26	39	22	40	24	36	24	42	20	25	23	11	17	30	17	14	13	18
5.ISC	29	38	26	40	27	36	27	41	23	29	26	11	19	29	19	14	14	18
6.FSC	26	33	22	34	24	31	24	36	20	25	23	9	17	26	17	12	13	15
7.MA	23	46	21	48	21	43	21	50	18	36	21	14	15	36	15	17	11	22
8.ACT	26	40	24	40	25	35	25	42	21	30	24	12	17	30	18	14	13	18
9.SR	27	41	25	43	26	38	26	44	22	32	25	12	17	32	18	15	14	19
10.CR	23	41	21	43	21	39	21	44	18	32	21	12	15	32	15	15	11	19
11.NE	14	29	14	30	14	26	14	42	12	21	14	8	10	22	10	21	8	13
12.NS	26	39	24	40	25	31	25	31	21	30	24	12	17	30	18	11	13	18
13.NW	29	57	26	59	27	53	27	62	23	47	27	17	19	45	20	14	14	28
14.UCW	31	50	28	52	29	45	29	54	25	40	28	15	20	39	20	18	15	24
15.LCW	27	54	25	56	26	51	26	58	22	44	25	16	18	42	18	19	14	26
16.SSl	22	36	20	37	21	33	21	39	18	27	20	8	15	28	15	13	11	17
17.ERi	31	28	28	29	29	26	29	30	25	21	28	10	20	21	20	10	15	13
18.SRi	32	40	28	42	30	37	30	44	26	31	29	12	21	31	21	14	16	19
Mean	26	40	24	42	25	37	25	44	21	31	24	12	17	31	17	14	13	19
Std Dev	4.1	7.7	3.4	8.0	3.7	7.4	3.7	8.4	3.2	6.3	3.5	2.5	2.5	6.2	2.5	2.8	1.9	8.0

7.3.2 Discussion

From the results in Table 7.4, it can be seen that for some districts, the planning distances in PBP and AS 3959-2009 are exceeded with the combined effect of vegetation and fire weather conditions. In general, for flat ground, PBP-2009 results in Table 7.3 are significantly lower than the calculated results in Table 7.4, with the exception of the New England (Armidale) District, and the Hunter-Macleay and Cumberland DSFs. The Coastal Valley Grassy Woodland is generally comparable to AS 3959-2009 but again, PBP-2009 underestimates the sustained flame lengths and radiant heat profiles with the notable exception of the New England (Armidale) District. Overall, FFDM5 sustained flame heights are lower than that of DEFFM, although with two vegetation classes (ST-DSF and Cu-DSF) the FFDM5 model gives higher sustained flame heights than DEFFM.

Considering the significant differences between rates of spread between the two models, there is a surprisingly close alignment between the two models in relation to flame length, although some distances may still be approximately two fold for DEFFM than FFDM5. An additional matter to note is that the differences between the Sydney Coastal and South-East DSFs and the two WSF are very small and it has been previously anticipated that for these vegetation classes, the differences in distances for radiant heat would be greater. This is also illustrated with the Hunter-Macleay and Cumberland DSF.

It is important to note that Table 7.7 above is for flat ground, and that with increasing slope this will exaggerate the differences between the two models, with a greater separation between the calculated distances (Sullivan et al, 2014).

7.3.3 Implications for construction practice and the 'design bushfire'

Under current construction practice, the deemed-to-satisfy provisions adopted through AS3959-2009, utilise a general fuel load, using the FFDM5 approach for forests and woodlands. The nature of 'deemed to satisfy' requirements, suggests that forests cannot be subdivided so as to provide greater differentiation on the basis of each surrogate used in the present study, let alone for the full suite of classes of WSF, DSF and GWs. Nor can AS3959-2009, provide for the use of the detailed fire weather conditions explored in the current study, although some improvements in the allocation of FFDI values to the fire weather districts can be undertaken.

In addition, a comparison of the FFDM5 and DEFFM models in relation to calculated fire behaviour and in particular flame heights will also need to be considered when revising AS3959-2009.

As reviewed in Chapter 2, the DEFFM model has only been used for dry sclerophyll forests and not for grassy woodlands or WSFs (Cruz et al, 2015a) until the current study. The same problem arises with the FFDM5 model which has not been verified for WSF or Grassy Woodlands, and further is considered inappropriate for predicting rate of spread of moderate to high fire conditions (McCaw et al, 2008) when compared to DEFFM.

It is of interest to observe from Table 7.4 that the Grassy/Shrub DSFs provide contradictory predictions. Both the Southern Tablelands and Cumberland DSF have higher setback for BAL-29 using the FFDM5 model over that of DEFFM for the GEV_{50} assessments. In contrast, the Hunter-Macleay DSF shows that DEFFM values are higher than FFDM5 model assessments at the GEV_{50} values. In some cases the DEFFM values (at 1:50 years) are not very different, although in other cases, they are approximately twice that of the FFDM5 results. These observations are the result of calculated flame heights with the inherent fuel structure characteristics incorporated into the DEFFM model.

DEFFM model is generally more conservative (from a safety perspective) than the FFDM5 model, however, this is not universal. One solution would be to take a mid-point within the range of the two values in Table 7.4 above.

Figure 7.1 below provides a plot of FFDM5 vs DEFFM 1:50 outcomes of flame height for a district across all 9 vegetation classes to determine if there is any clear correlation between the respective models. The sustained flame height plots were for the 9 vegetation classes using 15 highest ranked flame heights within each of the surrogate vegetation classes identified in Chapter 3.

Figure 7.2 below provides a plot of FFDM5 vs DEFFM sustained flame heights across a sample (15) of fire weather conditions (ranked by FFDI and used in GEV assessment) tested, with a single vegetation class (NC-WSF).

Correlation coefficients are low for both plots however there is greater correlation between vegetation (r^2=0.298) when compared to weather (r^2=0.126).

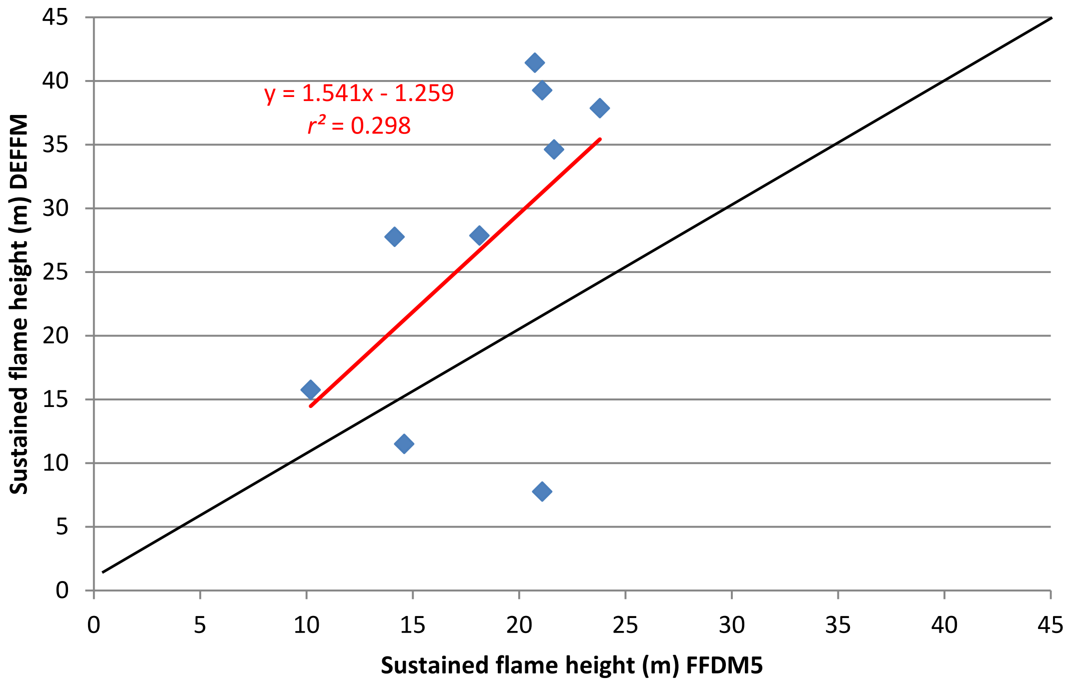


Figure 7.1: Comparison between FFDM5 and DEFFM of sustained flame heights for the Far North Coast for 9 vegetation classes.
(Black line is line of agreement, Red line is best fit)

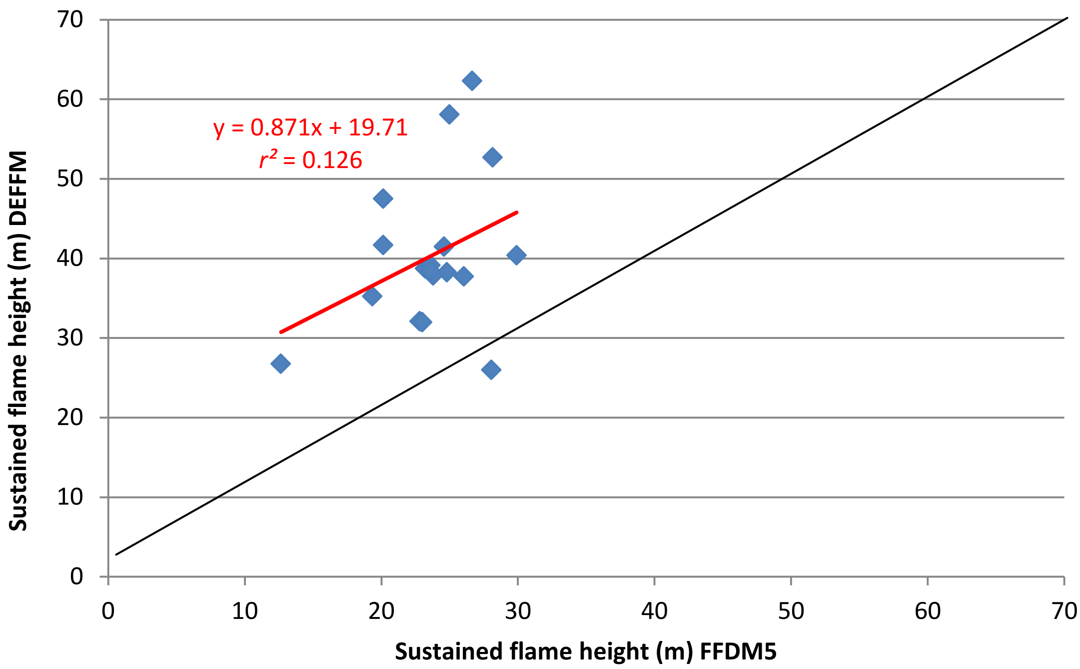


Figure 7.2: Comparison between FFDM5 and DEFFM calculated sustained flame heights for North Coast WS Funder 15 fire weather conditions
(Black line is line of agreement, Red line is best fit)

As can be seen from Figures 7.1 and 7.2, there is no clear relationship between FFDM5 and DEFFM across the vegetation classes or with the same weather conditions. This assumes that the assessments for fuel characteristics (DEFFM vs FFDM5) and fire weather conditions (FMC vs FFDI) are comparable between the two models. It can be seen that the DEFFM model generally predicts higher flame heights over both the weather conditions and vegetation classes used.

The two models use different sets of input data as well as different modelling approaches (see Chapter 2). A correlation between the outputs of the two models for a given return period is not therefore anticipated. This lack of correlation cannot be attributed solely to any one of the input parameters such as fuel load or vegetation classification but primarily exists as a result of the overall expressions and parameters used in rates of spread and flame height calculations.

7.3.4 Detailed consideration of results for Districts and broader landscapes in NSW

a) Wet Sclerophyll forests of the Coast and Tablelands of NSW sustained flame heights.

Districts 1-11 form the Coast and Tablelands (Ranges) areas of NSW, where there are more extensive areas of WSF, and the higher fuel load DSFs can be found. Figure 7.3 and Table 7.8 below illustrate the comparative sustained flame heights for WSFs in the Coast and Tableland areas of NSW.

Both the grassy and shrubby sub-formations can be found within each of these districts, although the extent of WSF rapidly diminishes as the districts move westward away from the coast and sheltered escarpments. Table 7.8 provides the averages of sustained flame heights for the two surrogate WSF vegetation classes and for 12 districts as well as the standard deviation of sustained flame heights for these vegetation classes. Due to small sample sizes, standard deviations have not been undertaken for district results.

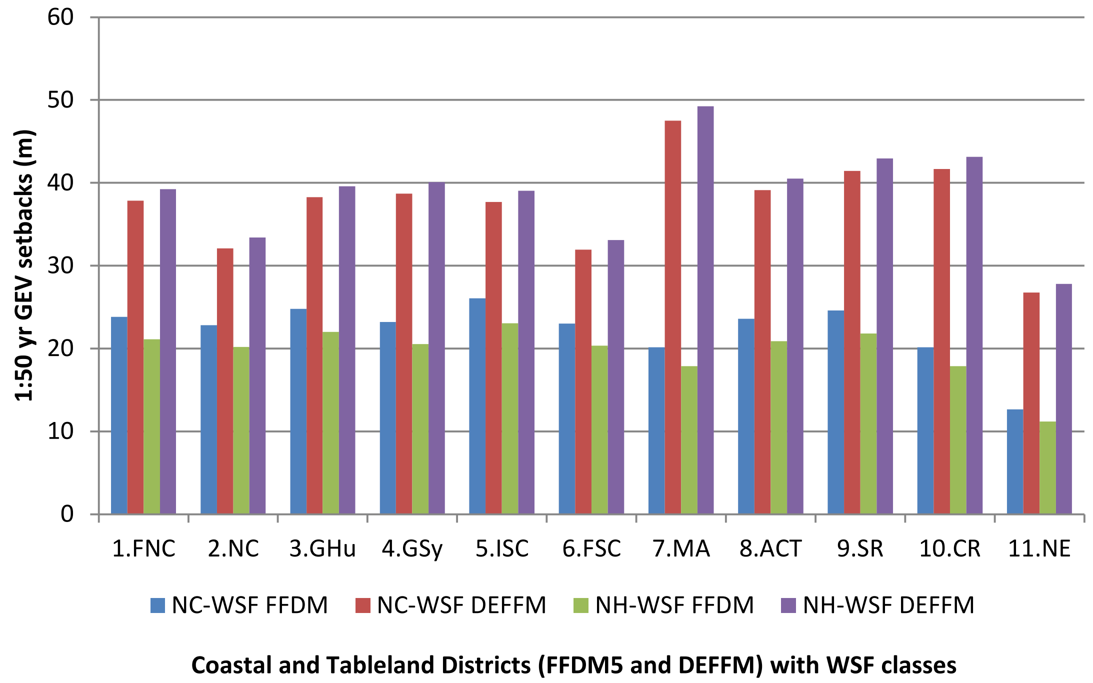


Figure 7.3: Comparison of GEV_{50} setback distances (BAL 29) of WSF between FFDM5 and DEFFM for coastal and tableland areas of NSW

Table 7.5: GEV_{50} BAL29 setback distances (m) for 2 surrogate WSF vegetation classes in Coastal and Tablelands Districts of NSW (Districts 1-11)

Fire Weather District	**NC-WSF**		**NH-WSF**		**Averages of both vegetation classes**		
	FFDM	DEFFM	FFDM	DEFFM	FFDM	DEFFM	Overall
1.FNC	24	38	21	39	22	39	31
2.NC	23	32	20	33	22	33	27
3.GHu	25	38	22	40	23	39	31
4.GSy	23	39	21	40	22	39	31
5.ISC	26	38	23	39	25	38	31
6.FSC	23	32	20	33	22	33	27
7.MA	**20**	**48**	**18**	**49**	**19**	**48**	**34**
8.ACT	24	39	21	41	22	40	31
9.SR	25	41	22	43	23	42	33
10.CR	20	42	18	43	19	42	31
11.NE	13	27	11	28	12	27	20
Vegetation Averages	22	38	20	39	21	38	30
Std Dev	3.7	5.6	3.2	5.8	3.4	5.7	3.9

In Table 7.5, the BAL results are considerably higher for the DEFFM than for FFDM5. The setback distances for the Monaro Alpine (7 Cooma) district (bold numbers) are higher than all other districts, which was unexpected, as this district has a lower FFDI value (at 1:50 year recurrence) than those found at the coast. The Central Ranges (10. Bathurst) has a comparable FFDI value (at 1:50 recurrence) but has a lower separation distance, arising from the individual weather parameters, rather than the combined FFDI.

All of the coastal areas (districts 1-6) from the Queensland border to the Victorian border have similar 1:50 GEV sustained flame height results, suggesting that the same prevailing wind and fuel moisture conditions exist for each of these districts. The higher wind values associated with the elevation of the district, appears to be a major driver for flame height and setbacks under these vegetation scenarios.

b) Dry Sclerophyll forests of the Coast and Tablelands of NSW sustained flame heights

The dry sclerophyll forests are the most extensive of the forest types across the NSW landscape (Keith 2004) and can be found across much of the coast and tablelands (districts 1-12) and extending to the Central parts of NSW, just short of the Western part of the State.

Table 7.6 and Figure 7.4 below illustrate the comparative setback distances for DSFs in the Coast and Tableland areas of NSW.

Both the grassy/shrubby and shrubby sub-formations can be found within most of these districts, although grassy/shrub DSF is absent in District 8. Table 7.6 provides the averages of 1:50 year GEV setbacks for the six surrogate DSF and one GW vegetation classes for the 12 districts as well as the standard deviation of setback distances for these vegetation classes. Due to small sample sizes, standard deviations have not been undertaken for district results.

As with the WSF, the 1:50 year GEV recurrence setback results using DEFFM are often, but not always larger than for the FFDM5 calculations. Again, the Monaro-Alpine District is notable in that DEFFM setbacks are the largest of those for other districts, whereas for FFDM5, the setbacks are at the lower end of the distances. Figure 7.9 shows the Monaro-Alpine values within the histogram.

Table 7.6: GEV$_{50}$ setback distances (m) for 7 surrogate DSF and GW vegetation classes for Coastal and Tablelands of NSW (Districts 1-11)

Fire Weather District	NC-DSF		SyC-DSF		SE-DSF		ST-DSF		HM-DSF		Cu-DSF		CVGW		District Averages		
	FFD M5	DEFF M	FFD M5	DEFF M	FFD M5	DEFF M	FFD M5	DEFF M	FFD M5	DEFF M	FFD M5	DEFF M	FFD M5	DEFF M	FFD M5	DEFF M	All
1.FNC	22	35	21	41	18	28	21	8	14	28	15	12	10	16	15.1	21	20.6
2.NC	21	29	20	35	17	24	20	9	14	24	14	10	10	13	14.5	18	18.6
3.GHu	23	35	22	42	19	28	22	9	15	28	15	12	11	16	15.9	21.3	21.2
4.GSy	21	35	20	42	18	24	21	9	14	28	14	12	10	16	14.8	20.8	20.3
5.ISC	24	34	23	41	20	28	23	9	16	28	16	11	11	16	16.6	20.9	21.4
6.FSC	21	29	20	35	18	24	20	8	14	23	14	10	10	13	14.6	17.8	18.5
7.MA	**18**	**43**	**17**	**52**	**15**	**35**	**18**	**12**	**12**	**35**	**12**	**14**	**9**	**20**	**12.6**	**26.4**	**22.3**
8.ACT	21	34	21	43	18	29	21	9	14	29	15	12	10	16	15	21.5	20.9
9.SR	22	38	22	45	19	30	22	10	15	30	15	13	11	17	15.8	22.9	22.1
10.CR	18	38	17	46	15	31	18	10	12	31	12	13	9	17	12.6	23.3	20.5
11.NE	11	25	11	42	10	20	11	6	8	20	8	19	5	11	8.0	17.9	14.8
Mean	20	34	19	42	17	27	20	9	13	27	13	12	10	16	14.0	20.9	19.9
Std Dev	3.4	5.1	3.3	4.7	2.8	4.2	3.2	1.4	2.2	4.1	2.2	2.5	1.6	2.3	2.3	3.0	3.1

The New England District (Armidale), has consistently lower setback distances and for FFDM5 but not for DEFFM. This appears to relate more to wind speed and FMC.

As previously observed, the Cumberland woodland and Southern tablelands DSFs indicate that setback distances are larger under the FFDM5 model, than that of DEFFM.

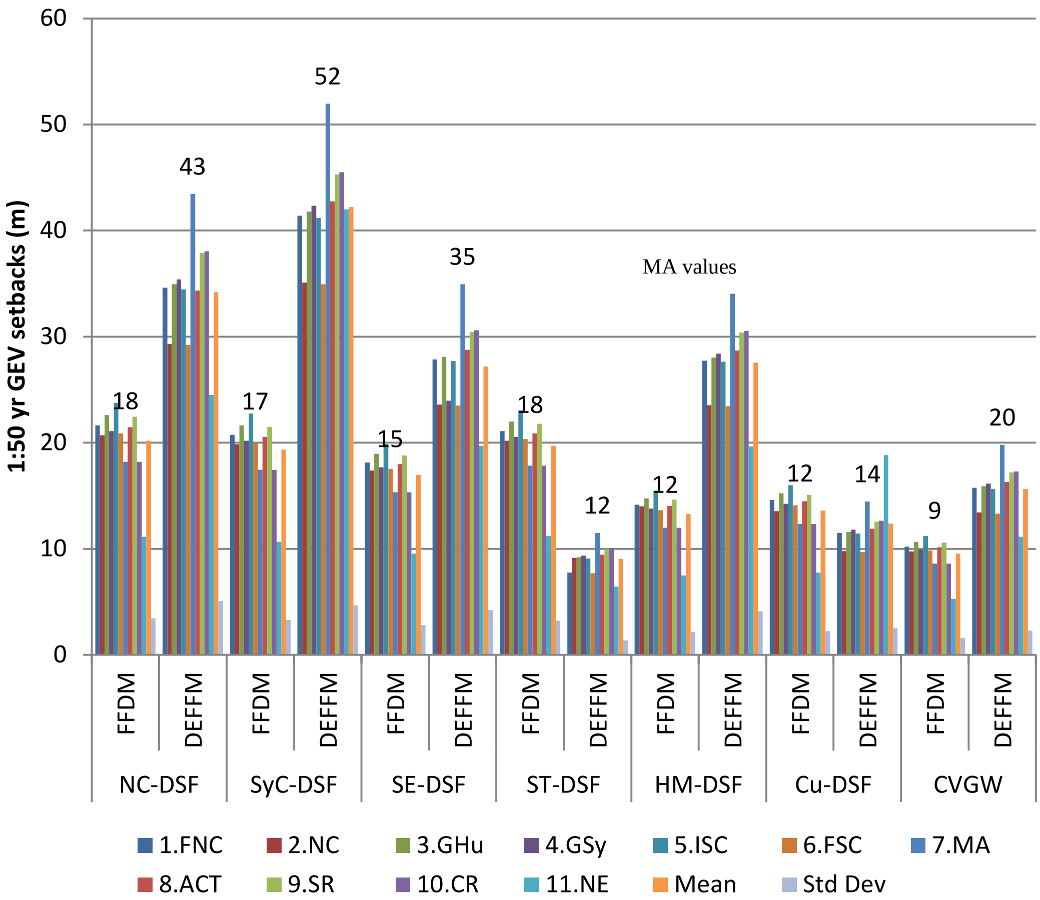


Figure 7.4: Comparison of GEV_{50} setback distances of DSF and GW between FFDM and DEFFM within coastal and tablelands areas of NSW

c) Dry Sclerophyll forests of Central NSW setback distances

It was noted previously, that there are no significant WSF classes in districts 12-18. These districts are all located within Central NSW. When considering the results for districts 12-18, the flame length and distances to 29kW/m2 radiant heat, are fairly close between some of the FFDM5 results (notably districts 11, 17 and 18) whereas the results for DEFFM provide quite variable distances and flame length outcomes, within the same districts.

The GEV_{50} results for setback distances of the (4) surrogate DSF and GW in districts 12-18 are illustrated in Figure 7.5 and Table 7.7 below. Figure 7.5 illustrates the variability between the FFDM5) and DEFFM setback distances. The results show similar setback distances within a forest class across the districts using the FFDM5 models, whereas, DEFFM setback distance results are much more variable within the vegetation classes and the districts.

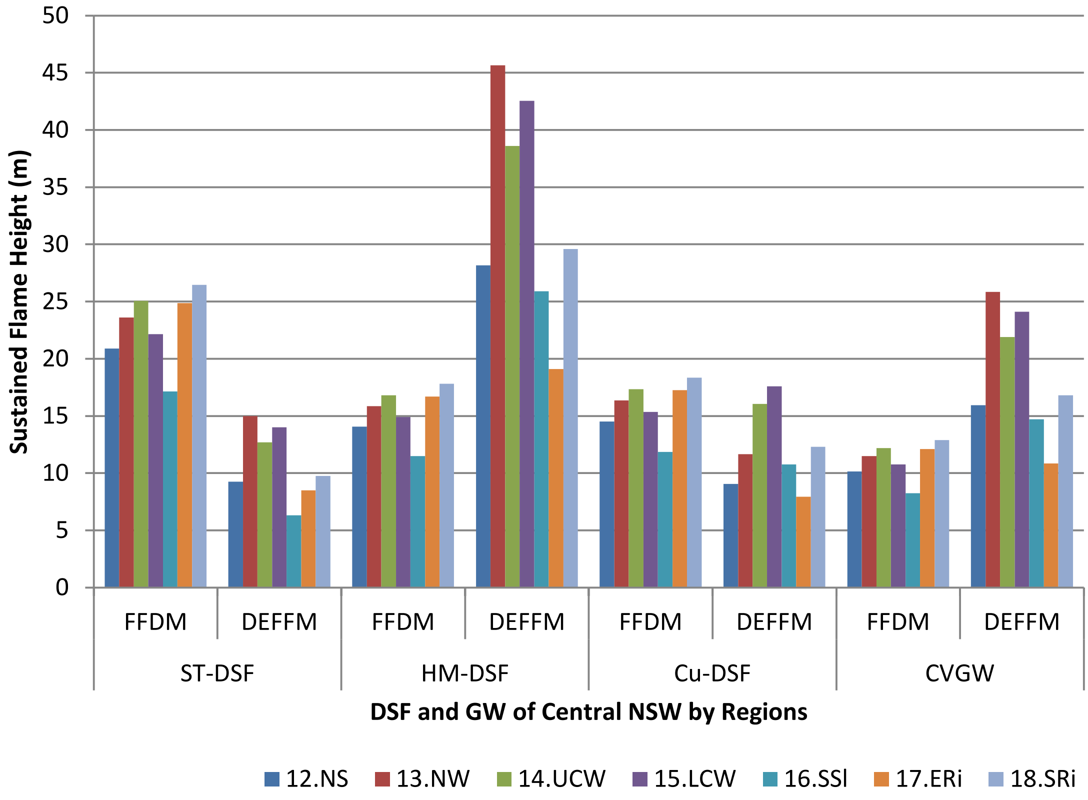


Figure 7.5: Comparison of GEV_{50} setbacks between FFDM5 and DEFFM within Central NSW

From Figure 7.3, it can be seen that the 4 surrogate DSF/GW vegetation classes used for Central NSW show some similarity using the McArthur model (FFDM5) as compared to the Project Vesta model (DEFFM). The actual resultant values and means (and standard deviation) of each vegetation class across the districts is shown in Table 7.7 below.

Table 7.7: GEV_{50} setback distances (m) for 4 surrogate DSF and GW vegetation classes for Central NSW (Districts 12-18)

District	ST-DSF		HM-DSF		Cu-DSF		CVGW		District Averages		
	FFD M5	DEFF M	FFD M5	DEFF M	FFD M5	DEFF M	FFD M5	DEFF M	FFD M5	DEFF M	All
12.NS	21	9	14	28	15	9	10	16	15	16	15
13.NW	24	15	16	46	16	12	12	26	17	25	21
14.UC W	25	13	17	39	17	16	12	22	18	23	20
15.LCW	22	14	15	43	15	18	11	24	16	25	20
16.SSl	17	6	12	26	12	11	8	15	12	15	13
17.ERi	25	9	17	19	17	8	12	11	18	12	15
18.SRi	26	10	18	30	18	12	13	17	19	17	18
Mean	23	11	16	33	16	12	11	19	16	19	15
Std Dev.	3.1	3.2	2.1	9.9	2.0	3.6	1.7	5.4	2.2	5.3	3.0

The largest setback distances are associated with the Hunter-Macleay DSF vegetation class across the districts, and the districts with the largest average setbacks are the North-West (Moree) and Lower Central West (Dubbo) for DEFFM, but is the Southern Riverina (Deniliquin) for FFDM5 (reflecting a high FFDI rather than fuel).

7.3.4 Summary

It is apparent that the coastal and tableland areas of NSW share similar fire weather conditions and fire behaviour, and as such, planning policy and construction practice needs to be amended to address this deficiency in those districts which currently do not have adequate protection. There are no clear relationships between the outcomes of the FFDM5 and DEFFM either in terms of vegetation classes or fire weather conditions. Rates of spread were consistently higher for DEFFM over that of FFDM5 of an order of 3 or greater, exceeding the findings of previous researchers (McCaw et al, 2008; Cheney et al, 2012) at the *extreme*.

However, the differences between flame heights varied considerably, with some vegetation classes exhibiting higher flame heights using DEFFM (notably WSFs), whereas in other cases flame heights were lower (as seen in some grass/shrub DSF). The DEFFM gave slightly higher flame heights than FFDM5 for grassy woodlands; however the differences were minor when compared to WSF vegetation classes.

The use of surrogate vegetation classes has provided a sound basis for comparative assessments; however, these vegetation classes do not represent all vegetation classes. Additional work on the grassy woodlands, particularly those associated with alpine and the far west of NSW is warranted as the current fuel assessments are likely to underestimate fire behaviour outcomes.

The investigations discussed within this chapter have been limited to the simplest of scenarios. The scenarios assume flat terrain and are limited to 9 surrogate vegetation classes. Further investigation for other classes is warranted but is contingent on availability of elevated and near surface fuel height data, not currently available.

BAL29 distances have been determined on the basis of whole numbers distances from the potential fire front, at or beyond which the radiant heat flux from the fire is no more than 29 kW/m^2. This is in line with the methodology adopted in AS 3959-2009.Most distances (for BAL29) exceed that of PBP and AS3959-2009.

From a methodological perspective, it has also been feasible to undertake the investigations to date based on the use of simple equations and the use of common software (Excel(R)), allowing practitioners or other researchers to apply the GEV approach using available data.

In Chapter 1, it was hypothesised that flame heights for the FFDM5 and DEFFM models would provide similar results. The results of this Chapter indicate that flame heights are of a similar order to each other but that there is no clear bias between the two models, and it cannot be said they are of sufficiently similar dimensions so as to yield comparable distances for radiant heat calculations. This arises from the fuel characteristics used in the model. Whereas rates of spread are consistently faster in the DEFFM model over FFDM5, flame heights may be higher or lower, dependent on fuel characteristics (notably elevated fuel heights).

The adoption of the DEFFM model would therefore have important implications for construction practice, over the use of the existing FFDM5 model, adopted within AS 3959-2009.

CHAPTER 8- FIRE WEATHER PARAMETERS UNDER THE INFLUENCE OF CLIMATE CHANGE.

8.1 Introduction

In Chapter 4, it was identified that under the influence of climate change, global climatic models (and regional variants) are strongly suggestive of impacts on the global weather system which could give rise to increased fire danger conditions (reflected in FFDI). These changes to fire danger may be occurring at least through a general trend towards more frequent and deeper drought periods (as measured by KBDI) in spite of a slight increasing trend in SOI (i.e. to wetter conditions, see Section 4.2.6).

It is uncertain at this time, what the overall effect of inter-decadal climatic influences, such as SOI, has in relation to climate change, even if there is a strong relationship between adverse fire years and the onset of the ENSO(Williams and Karoly, 1999). A statistical approach will need to be considered to address the relationship that ENSO has with FFDI, FMC, KBDI and climate change.

Since FFDI, FMC and KBDI are the important indicators of fire weather (see Chapter 2), the impact of climate change on these parameters will need to be investigated in this chapter. In addition, the role of ENSO as a possible confounding factor will also be explored. Together these four parameters (FFDI, FMC, KBDI and ENSO) may give rise to altered states of fire weather arising under the influence of climate change.

8.2 Methods of Analysis

It has already been ascertained by previous investigations (Hasson et al, 2008) that fire weather conditions, and hence fire behaviour will alter in the future as the effects of climate change will become more pronounced (and hence severe) over time. However, the possible extent of such changes has not been quantified.

Katz et al (2005) noted the potential advantages of *extreme* value theory when modelling ecological disturbances. Such approaches can be combined with moving average methods to detect shifts among alternate states through non-linear methods (Ives and Dakos, 2012).

These principles are to be explored in considering the potential for shifts in weather and climate (i.e. climate change) in this chapter.

8.2.1 Previous methods and datasets

Previous studies (Hennessey et al, 2005; Lucas et al, 2007) described changes in annual average cumulative FFDI (denoted ∑FFDI) under different climate change scenarios using GCM (CSIRO's CCAM Mark 2 and CCAM Mark 3).This is described in Chapter 4. The studies by Hennessey et al (2005) generated weather data from computer simulations of FFDI which may have had the effect of over or under-representation. Lucas et al (2007) used historical data for the period 1974-2003, and predicted changes also using GCM. They also considered monthly-average FFDI and daily-average FFDI. The Hennessey et al (2005) study did consider the number of events per year which exceeded very high (FFDI≥25) or severe (i.e. FFDI≥50) over the period of data. Changes using FFDI as an indicator in modelled GCM scenarios, provided some insight into possible shifts in fire weather. Such measures do not address climate change impacts in terms of recurrence at the *extreme* however. These two previous studies covered 8 sites used within the current study. These 8 sites are shown in Table 8.1.

Table 8.1: NSW weather stations used in previous (Lucas et al, 2007)and current studies

Weather District No.	Weather District Name	Weather Station
2	North Coast	Coffs Harbour
3	Greater Hunter	Williamtown
4	Greater Sydney	Sydney
5	Illawarra /South Coast	Nowra
8	ACT	Canberra
13	North Western	Moree
15	Lower Central West	Dubbo
17	Eastern Riverina	Wagga Wagga

The Lucas et al (2007) study provided an assessment of annual average ∑FFDI, average number of days of FFDI≥25, and average number of days of FFDI≥50 for the period 1973-2007 and the predicted increases in these metrics to 2020 (using GCM).

8.2.2 Approaches to the current study

The impact of climate change on fire weather conditions, may be reflected not only on increased fire weather severity, but also on the potential frequency of fire events, or the duration of the fire season.

In Chapter 1, it was hypothesised that on current evidence:

- The changes in annual and seasonal fire weather is likely to be extended in New South Wales. If this occurs, there will be an increased period for bushfire in a given fire district each season (Clarke et al, 2012);
- *Extremes* of fire weather events will increase at a given recurrence period (1:50year) due to climate change;
- Design bushfires based on the McArthur (FFDM5) and Project Vesta (DEFFM) models will provide similar outcomes for land-use planning and construction in forested areas of New South Wales; and
- A more robust method can be used for selecting design bushfire scenarios with consideration of different fire weather parameters.

In the current study, a number of methods were employed to reveal the effect of climate change on fire weather parameters using data for a longer period than previously studied to consider the proposed hypotheses.

The first method is to analyse shifts in annual (and seasonal) average cumulative fire weather parameters over a moving 4-year window traversing through the extended period of data available. The averaging of a cumulative parameter over a moving window allows strong fluctuations to be smoothed out, leaving a discernible trend of variation, whilst retaining sensitivity to those variations, not apparent in mean values. The 4-year moving window width is able to include one leap year within each cycle such that the number of days in a window are the same within each cycle. The 4 year moving average was not considered by Hennessey et al (2005) or Lucas et al (2007), using cumulative values as described above. Moving averages allows peaks and troughs to be averaged to detect dynamic changes (Ives and Dakos, 2012).

To ascertain the potential impact of climate change on fire weather, changes in annual frequency of days per year exceeding identified threshold values are analysed. This analysis forms the second method employed in the current study.

The first two methods used to analyse both changes in the frequency of fire weather events, as well as shifts in seasonal conditions, leading to longer duration in fire season. The second of these two methods is related to fire weather severity, although increased frequency of events, is also likely to see increased severity.

Severity, however, is best measured at the *extreme*. In order to consider changes in fire weather severity, the third method is introduced. This method uses the GEV assessment and prediction of the 50 year recurrence value of fire weather parameters based on a moving 20 year data window over the data period. The 20 year window is considered the minimal number of years required for reasonable accuracy for prediction of comparable recurrence values (see Gumbel, 1958).

Climate change may be disguised through broader global climatic events. These broader climatic events (such as ENSO and IOD) give rise to variable conditions or arise at various timeframes. ENSO may either promote adverse fire weather conditions, or be a confounding factor, disguising the impacts of climate change.

The fourth method (metric 4) considers the relative correlation between SOI and fire weather parameters. A high correlation between SOI and fire weather would suggest the SOI is a more dominant factor in fire weather. Conversely a low correlation would suggest that SOI is not a major determinant of fire weather over the long term. It may still have an effect during the actual ENSO event. A negative correlation indicates that climate change is more likely to be a dominant factor in fire weather than SOI.

Due to the lack of continuous data for all weather stations, some metrics can only be considered for the extended National Fire Weather Dataset (Lucas, 2010). This is particularly important for the 20 year moving GEV_{50}, as the NSW dataset only provides 21 years of data (see Section 5.3.2).

Table 8.2 provides an overview of the methods of analysis used for the present investigations for the various parameters which influence fire weather conditions.

Table 8.2: Methods of analysis used to measure impact of climate change on fire weather

Parameter	Metric 1	Metric 2	Metric 3	Metric 4
	Changes in Annual and Seasonal Average (4 year moving)	No. of days above/below threshold (4 year moving)	GEV_{50} (20 year moving)	Pearson's Correlation
FFDI	∑FFDI	FFDI≥25 FFDI≥50	FFDI	Monthly ∑FFDI with Monthly SOI
FMC	∑FMC	FMC≤7%	FMC	Monthly ∑FMC with monthly SOI
KBDI	∑KBDI	KBDI≥150	KBDI	Monthly ∑KBDI with Monthly SOI

The first two metrics will be applied to all 18 NSW weather station sites and include the 8 sites used in the previous study of Lucas et al (2007). The 50 year recurrence FFDI in the 3rd metric is obtained by applying the GEV modelling at the 20 year moving data period for the 43.5 years of data. This approach was also applied to FMC and KBDI. KBDI was generally found to have numerous consecutive days (in early 1983) at the highest values. As such, for KBDI, the highest rank values result in a repetitive GEV_{50} recurrence. The use of Gumbel (Amax), was also considered, however this was likewise of little use as many sites would yield results in excess of the maximum of 200mm for KBDI at the 50 year recurrence.

The data for the 8 National Historical dataset runs from 1 June 1972 to the end of 2015. Because the extended data is available for the eight sites identified in the two previous studies by Hennessey et al (2005) and Lucas et al (2007), Metric 4 is only applied to these sites listed in Table 8.1. The assessment of FFDI, FMC and KBDI with SOI has also only been assessed for the 8 NSW sites identified in Table 8.1. The SOI data was only available for the period up to 2009, so the correlation was only undertaken for the period 1972-2009.

To measure trend, data is subject to linear least-squared assessment and the trend line established for all data in the assessed time series. The trend lines can be expressed as:

$$F=S(x-x_o)+b \qquad (8.1)$$

where

F is the regression or trend value of any fire weather parameter measured (see Table 8.2),

S is the slope of the trend line,

x is the calendar year,

x_o is the year of period starting, and

b is the initial trend value F at $x=x_o$.

The slope of the trend lines and the correlation coefficient of the line fit r^2 are analysed.

8.3 Climate Change and FFDI

8.3.1 Methods of analysis

FFDI is a good indicator of fire weather being a function of drought, temperature, humidity and wind speed. In this section, Metric 1, Metric 2 and Metric 3 described in Table 8.2 have been analysed for FFDI to assess potential impacts on fire weather under the influence of climate change. These metrics are:

- changes in annual and seasonal ∑FFDI over a four year moving average;
- changes in frequency and annual average of FFDI$\geq$25 (and $\geq$50) thresholds; and
- changes in recurrence of FFDI at the *extreme*.

Should trends in FFDI Metric 1increase, this would indicate that fire weather frequency is likely to be increasing. Metric 2 can be used to measure whether fire seasons are lengthening, and Metric 3 can quantify if fire weather severity is rising. Negative values for trends in these metrics does not in itself mean that climate change is not having an impact, however lower FFDI metrics may be associated with increased rainfall or changes in other weather parameters.

8.3.2 Changes in annual and seasonal ∑FFDI

Metric 1, namely the analysis of annual and seasonal changes in ∑FFDI, was undertaken for all 18 NSW sites used in the study. An example of the plot of the data for Coffs Harbour is shown in Figure 8.1 below. These plots of the 4 year progressive (moving) data has been annualised so as to remove the peaks and troughs associated with one-off conditions and/or factors associated with ENSO events. It can be seen that while there is some degree of cyclic variation, there is a steady increase in ∑FFDI for all seasons (and consequently annually).

It can be seen that each progressive cycle in the data shows an elevated ∑FFDI and that the spring and winter periods are largely dominant for the shifts associated with these changes in Coffs Harbour. In contrast, the same plot for Sydney (Figure 8.2) shows a dominance of spring and summer changes in ∑FFDI.

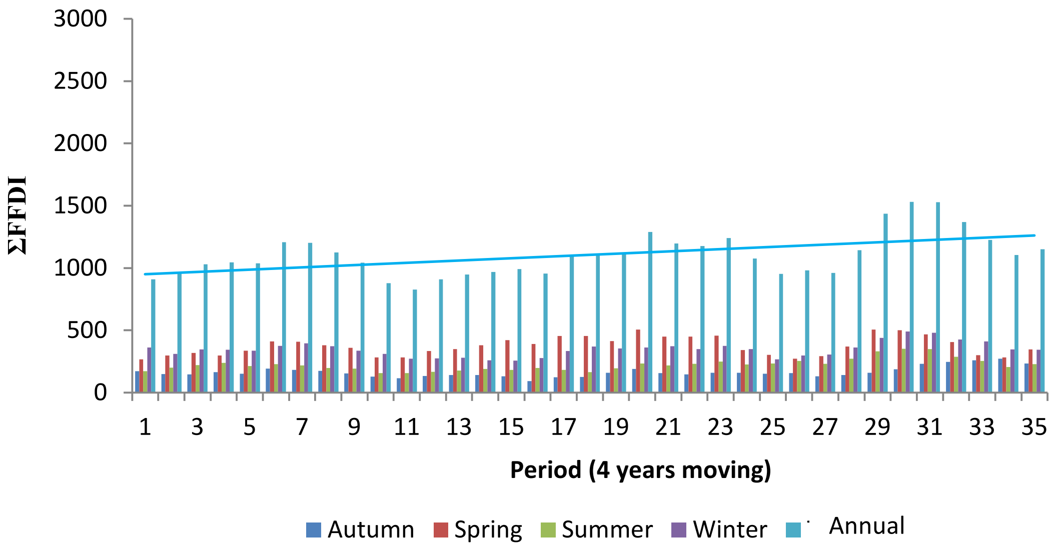


Figure 8.1: 4 year progressive average of annual and seasonal ∑FFDI for Coffs Harbour (with trend line).

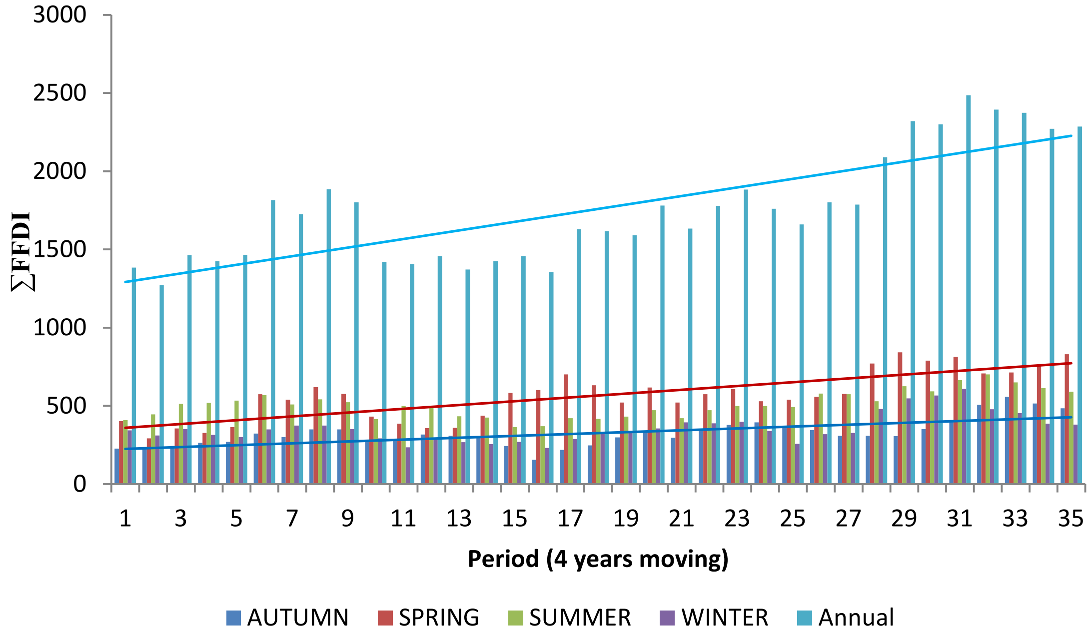


Figure 8.2: 4 year moving annual and seasonal ∑FFDI for Sydney (showing regression line for annual, autumn and spring).

Although both Coffs Harbour and Sydney are increasing both seasonally and annually, it can be seen that Sydney (Figure 8.2) is increasing at a greater rate than Coffs Harbour (Figure 8.1). The changes in the FFDI during autumn and spring periods in Figure 8.2 suggests that the bushfire season (normally expressed as October to March) is expanding, and that the onset of FFDI values of higher magnitudes may be increasing within the non-bushfire season. In conjunction with changes in FFDI exceeding thresholds (of FFDI≥25 or ≥50), the increases in ∑FFDI can be used to consider whether bushfire seasons are expanding.

Table 8.3 provides a list of linear regression slope *S* and correlation coefficient of 4 year moving average for annual and seasonal ∑FFDI for NSW fire weather districts.

Table 8.3: Summary of trends (*S*)and correlation coefficient for 4 year moving annual and seasonal ∑FFDI

Weather Station	Annual Average ∑FFDI	Autumn		Spring		Winter		Summer		Annual	
		S	r^2	*S*	r^2	*S*	r^2	*S*	r^2	*S*	r^2
Grafton[a]	2200	-1.9	0.05	-11.0	0.06	-3.0	0.02	-7.4	0.10	-22	0.07
Coffs Hbr	1106	2.0	0.25	1.9	0.07	2.2	0.15	2.9	0.35	9.1	0.29
Williamtown	1832	0.3	0.00	8.0	0.28	4.0	0.28	3.0	0.10	15.2	0.29
Sydney	1759	5.9	0.48	12.1	0.64	4.9	0.48	4.5	0.30	27.5	0.64
Nowra	1687	8.1	0.77	11.0	0.53	4.2	0.3	2.5	0.09	25.8	0.59
Batemans Bay[a]	1505	6.1	0.05	17.1	0.14	-3.5	0.02	3.12	0.01	22.8	0.09
Cooma[a]	2895	34.4	0.55	42.3	0.77	13.8	0.37	59.9	0.82	150	0.80
Canberra	3239	12.0	0.52	5.9	0.10	1.5	0.08	1.7	0.01	21.2	0.18
Goulburn[a]	3194	8.9	0.08	53.4	0.77	14.0	0.50	20.4	0.29	96.7	0.84
Bathurst[a]	2617	10.4	0.05	32.2	0.40	7.9	0.26	2.3	0.01	52.8	0.18
Armidale[a]	1469	0.4	0.00	12.1	0.36	4.6	0.19	8.8	0.19	25.9	0.32
Tamworth[a]	3876	11.5	0.09	41.5	0.39	6.3	0.08	37.6	0.57	96.9	0.53
Moree	2983	8.8	0.41	12.3	0.28	4.8	0.29	12.4	0.14	38.3	0.29
Coonamble[a]	4449	29.9	0.42	78.4	0.56	18.5	0.30	76.0	0.62	203	0.64
Dubbo	3049	16.6	0.50	19.9	0.47	5.9	0.37	30.5	0.71	72.8	0.67
Young[a]	3650	29.7	0.39	65.3	0.76	7.8	0.33	41.0	0.63	144	0.77
Wagga Wagga	8562	15.3	0.59	16.0	0.35	10.7	0.18	71.8	0.34	114	0.40
Deniliquin[a]	4563	53.3	0.84	103.1	0.7	24.9	0.87	98.2	0.86	280	0.86
a. data only for the period 1994-2009.											

As the data for the 8 weather stations used by Lucas et al (2007) commences on 1/5/1972 (i.e. beginning of winter), this date has been used as the starting point for all assessments for this metric. The summer period is taken as December-January-February (DJF) seasonal period, rather than January-February and December of the calendar year. For the remaining 10 weather station, the data commences on 1 January, and the progressive period commences on 1 March, with the period being annualised from that point, again with summer commencing on 1 December.

Table 8.3 suggest that the cumulative annual FFDI in most weather districts in NSW is increasing ($S>0$) though with different rate and variability. Therefore, fire weather can be anticipated to be more severe in some districts in the future. The ∑FFDI of inland areas (refer to Table8.3) have the higher increasing trends than coastal areas and relatively lower variability.

The exception was Grafton weather station (shaded in Table 8.3) which has a negative trend for ∑FFDI ($S<0$) with a very low correlation coefficient. This site has an opposite trend from all other stations, with a highly variable annual FFDI, which also influences the 4 year moving values.

The Far North Coast is known to be highly influenced by the onset of the northern monsoon period, which will have an effect on rainfall and therefore fuel moisture and KBDI. This can also be deduced from the high negative spring and summer values most often associated with the onset of the northern monsoon.

A summary and comparison of the results from Hennessey et al (2005), Lucas et al (2007), Clarke et al (2013) and the current study are shown in Table 8.4.

Table 8.4Comparison between Current and Previous Studies in ∑FFDI[#]

Weather Station	Hennessey et al (2005)[a]		Lucas et al (2007)[b]		Clarke et al (2013)[c]	Current Study[d]	
	∑FFDI[#]	Change*	∑FFDI[#]	Change*	∑FFDI[#]	∑FFDI[#]	Trend
Coffs Hbr	2002	5-12%	1255	3-11%	1167	1106	9%
Williamtown	2641	5-13%	1984	4-14%	1914	1832	15%
Sydney	2158	5-12%	1897	4-11%	1897	1759	27%
Nowra	2507	4-13%	1768	2-12%	1762	1687	26%
Canberra	2913	10-26%	2493	9-30%	2417	3239	21%
Dubbo	N/A	N/A	3153	11-34%	3577	3049	73%
Moree	N/A	N/A	3937	12-37%	4198	2983	38%
Wagga Wagga	4047	9-23%	3319	9-29%	3461	8562	114%

a. Data from 1974-2003,b. Data from 1973-2006,c. Data from 1985-2009, d. Data from 1972-2009

* GCM 2020-2050predicted increase CCAM (Mark 2). High rates of global warming.

annual average cumulative FFDI.

The trends within the current study, confirm that of previous studies using predictive techniques, although the trends of the current study are higher further inland than that of predictive studies for overall annual average of ∑FFDI. The results of the current study are already at the higher end of the predictions using GCM.

Each of these studies used slightly different data sets, but are based on the dataset prepared by Lucas (2007), which is constantly being updated. It can be seen that the trends of the current study using empirical data exceed that of the computer (GCM) predictions by Hennessey et al (2005) and Lucas et al (2007). The study by Clarke et al (2013) did not attempt to predict future trends, but rather assess the skill of the WRF model and is used for comparisons with Lucas et al (2007) and Hennessey et al (2005) for the same period.

For the 4 year moving ∑FFDI used in the current study, there is a consistent pattern of increasing FFDI over the period of the data (1972-2015) with the only exception being for Grafton which has a negative change for all seasons and annually. The increases are less pronounced along the coast, with greater increases seen further inland.

8.3.3Changes in annual frequency of FFDI exceeding thresholds and corresponding cumulative FFDI

The frequency of higher FFDIs can be assessed to determine likely seasonal variations under the influence of climate change (and possibly ENSO). Assuming dynamic environmental conditions (i.e. climate change), the frequency (or average) number of FFDI days exceeding thresholds can be expected to rise, or alternatively, the frequency may be static, however, the ΣFFDI (sum FFDI) within the frequency of events may rise. A 4 year moving frequency assessment for FFDI≥25 and FFDI≥50 was undertaken, in conjunction with a trend analysis for the period 1994-2015.

Figure 8.3 illustrates the plot of the data and trend line (linear) for the 4 year moving FFDI threshold exceedance and sum (∑) of the FFDI values equalling or exceeding FFDI 25. The year is given as the last year in the 4 year sequence.

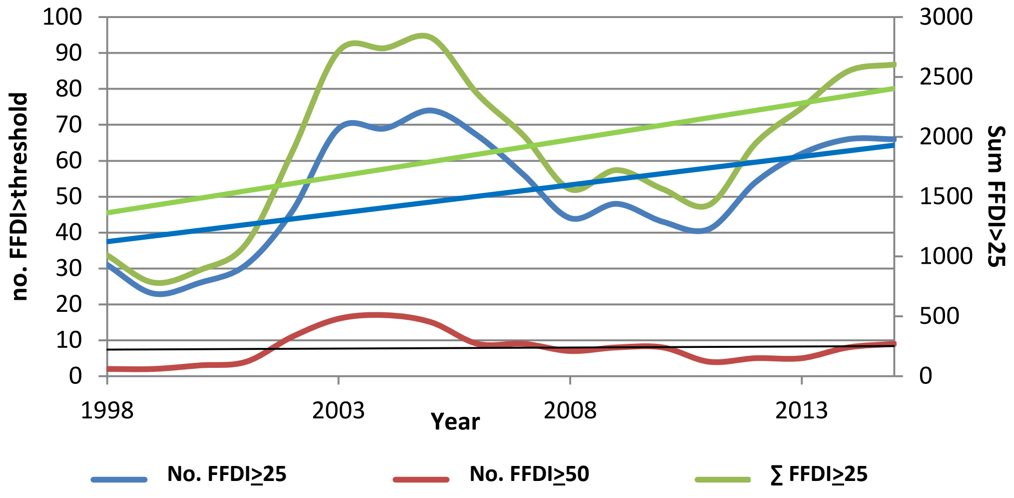


Figure 8.3: Trend in Frequency of exceedance of FFDI≥25 (and ≥50) and ∑FFDI≥25 for Williamtown.

It can be seen from the Figure 8.3that (for Williamtown) the threshold values of FFDI≥25 and FFDI≥50 increase over the time period and that the ΣFFDI values (for FFDI≥25) follows the same pattern as frequency (no.) of FFDI≥25, and all values are rising. The rise in ∑FFDI is therefore mostly associated with increased frequency of days exceeding the FFDI≥25 threshold.

Table 8.5 provides a summary of the trend analysis for the 4 year moving results of threshold exceedance for FFDI (>25 and >50) and ΣFFDI >25, for the 18 stations used in the present study. The trend is taken from the regression for the period assessed (1994-2015). This period was selected as this period was available for all sites in the current study.

Appendix 14 provides the detailed results for the moving 4 year assessments summarised in Table 8.5.

Table 8.5: Summary of Trends (*S*) in FFDI exceeding Thresholds (>25 and >50) and ∑FFDI>25 (1995-2015) using 4 year moving averages.

Weather Station (Fire Weather District No.)	Av No. Days FFDI>25/yr	Trend No. of Days FFDI>25	Trend No. of Days FFDI>50	Trend ∑FFDI>25
Grafton (1)	5.7	-1.073	-0.205	-40.38
Coffs Hbr (2)	1.4	0.147	-0.074	-5.44
Williamtown (3)	12.7	1.576	0.059	61.03
Sydney (4)	10.1	1.278	0.566	63.52
Nowra (5)	9.4	0.027	0.157	12.21
Batemans Bay (6)	3.9	0.245	0.883	34.95
Cooma (7)	18.6	1.797	0.318	67.38
Canberra (8)	19.4	-1.216	0.105	-35.72
Goulburn (9)	25.6	-2.421	-0.252	-85.50
Bathurst (10)	15.5	1.621	-0.046	51.18
Armidale (11)	0.3	-0.082	NA	-2.20
Tamworth (12)	27.2	0.962	0.492	48.52
Moree (13)	29.2	8.216	1.123	311.10
Coonamble (14)	46.5	9.669	1.783	383.00
Dubbo (15)	38.5	2.853	0.678	114.90
Young (16)	31.3	-0.540	-0.129	-13.12
Wagga (17)	42.5	1.980	0.653	99.97
Deniliquin (18)	52.4	10.620	2.422	443.40

From Table 8.5 it can be seen that the frequency of and cumulative threshold FFDI values are increasing over time for most stations and that the extent of changes increase from the coast and at lower latitudes. The trends show that increases in frequency of FFDI>25 are greatest in the Central West, of NSW (Dubbo, Coonamble and Moree) whereas the results indicate a negative result for the Southern Ranges (Canberra and Goulburn), Far North Coast (Grafton), and New England (Armidale).

Overall, the results indicate that the pattern of threshold exceedance and 4 year movingΣFFDI (for FFDI>25) follow a similar pattern of changes to that of frequency values. The relative increases for the frequency in FFDI≥50 is lower than that for FFDI≥25. Coffs Harbour weather station shows a lower frequency values for FFDI>50, while FFDI>25 increases, which may be associated with a lowering of seasonal fire weather conditions seen in Grafton.

The largest rises are associated with the western areas of the State, with modest positive or negative results for higher elevated areas such as the Central (Bathurst), Southern (Canberra and Goulburn), New England (Armidale) and Northern Ranges (Tamworth). Coastal areas generally have a small increases, however, northern coastal areas (Grafton and Coffs Harbour) show some negative trends.

Table 8.6 provides a comparative assessment of the results for numbers of days exceeding an FFDI≥25 for the current study and that of previous investigations. This table includes the results from the Hennessey et al (2005) study and the Lucas et al (2007) study for present and future (2020) predictions using two GCMs (CCAM Mark 2 and CCAM Mark 3), assuming high rates of CO_2 emission scenarios. These two studies have a different periods for the weather datasets, and differ from the current investigation. For the present study, predicted values are based on empirical data and regression lines as opposed to computer simulations (based on GCM).

Table 8.6Comparison between Current Study and Previous Studies on Average Days per year with FFDI≥25 and predicted for 2020

Weather Station	Hennessey et al (2005)[a]		Lucas et al (2007)[b]		Current Study[c]	
	Present	Predicted	Present	Predicted	Present	Regression
Coffs Hbr	4.4	5.1-5.6	1.5	1.8- 1.8	1.4	2.0
Williamtown	16.4	18.2-19.4	10.3	11.5 -12.8	12.7	18.8
Sydney	8.7	9.8-11.1	7.6	8.3-9.4	10.1	15.1
Nowra	13.4	14.7-15.6	8.8	9.2-10.3	9.4	9.5
Canberra	23.1	27.5-28.6	16.8	21.5-22.8	19.4	14.7
Dubbo	N/A		23.0	30.0- 29.2	38.5	50
Moree	N/A		30.5	41.1- 38.9	29.2	61
Wagga Wagga	49.6	57.3-57.4	32.6	39.7- 40.3	42.5	50

a. Data from 1974-2003, b. Data from 1973-2006. c. Data from 1994-2015.
Predicted values for Hennessey et al (2005) and Lucas et al (2007) using CCAM-Mark 2&3, with high rates of global warming.

From the results in Table 8.6, it can be seen that there is better alignment of the results for the current study with the results of Lucas et al (2007) than that of Hennessey et al (2005), although current study results for Williamtown and Sydney, align better with Hennessey et al (2005).

Canberra has lower values within the current study than the present situation and has a negative regression compared to all other sites. Notwithstanding the results for Canberra, it can be seen that there is a general trend to increased frequency of days exceeding FFDI$\geq$25.

Although these results assist in understanding changes in seasonal fire weather conditions (see also discussion on seasonal ΣFFDI above), it does not confirm that there are changes at the *extreme* values which are critical for determining design bushfire conditions.

It is, therefore, necessary to undertake a GEV (or similar) assessment so as to ascertain whether the *extreme* FFDI values (in this case at 1:50 year recurrence) are increasing.

8.3.4 Changes in 50 year recurrence FFDI

In this subsection, Metric 3 in Table 8.2 is used to determine the progressive GEV_{50} for FFDI using the 20 year moving average.

This process was undertaken for each of the 8 National Fire Weather Datasets (Table 8.1) by assessing the first 20 year data period and then shifting by 1 year and applying the GEV assessment to each of the 24 periods (of 20 years) available. This assessment could not be applied to the 10 NSW Historical dataset stations as they only comprise 21 years of data (see Chapter 5).

An example of the plot of a series of moving 20 year GEV values was undertaken and can be seen in Figure 8.4 for Coffs Harbour below.

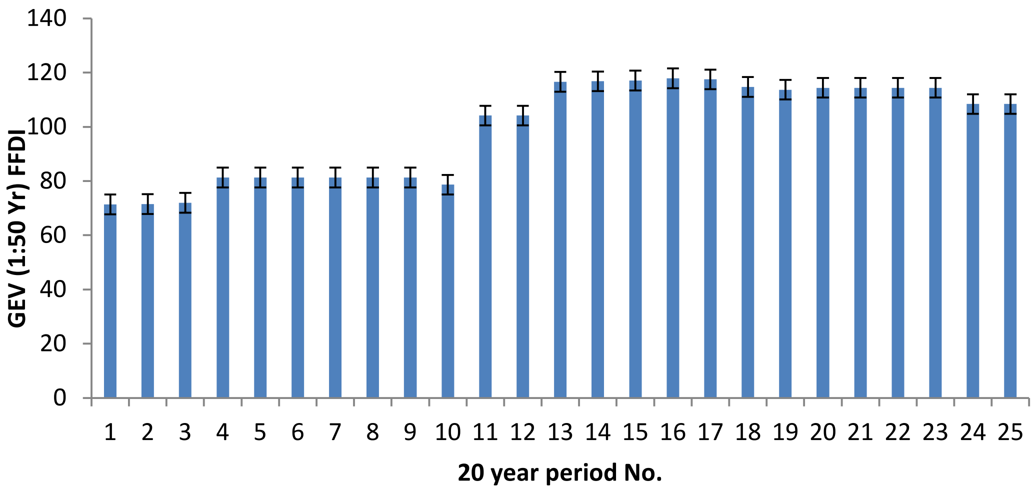


Figure 8.4: 20 year moving GEV_{50} FFDI plots (with S.E.) for Coffs Harbour

As can be seen, the GEV_{50} assessment for Coffs Harbour indicates that the 20-year moving FFDI values have increased from approximately 70 in the first period to nearly 120 in the last. The significant jump occurred in the 11th period, or the period including the year 1983 when the historical Ash Wednesday fire event took place. It should be noted that this periodis associated with a strong ENSO and IOD event.

Also note that the GEV_{50} FFDI based on the entire 43.5 year data period (1972-2015) was estimated in Chapter 6 to be 95. This illustrates the importance of undertaking both overall and latter period assessments as the use of GEV based on the 43.5 years of data alone, may under-estimate the overall trend observed compared to the last 20 years.

The extent of this change in the GEV_{50} for FFDI alters within each fire weather district (as represented by a weather station) with 43.5 years of data, using a 20 year moving GEV value.

Table 8.7 provides a summary of the 20 year moving averages GEV_{50} values for each of the 8 NSW weather stations identified in Table 8.1.

From Table 8.7 it can be seen that for most sites, the trend in $GEV_{50}$for FFDI is increasing over the period. The major exception to this can be found with the Williamtown weather station, where the trend is clearly declining. Nowra has an overall negative trend, however, the final years recurrence values are higher than the initial years values. There is also a dip in the recurrence period during the period starting 1984-1989. This then rises again after the period starting 1995, with the exception of Coffs Harbour, which consistently rises over the full period.

Table 8.7: 20 year moving GEV_{50} FFDI for 8 fire weather stations showing mean and overall GEV_{50} values

20 year period	Coffs Hbr	Williamtown	Sydney	Nowra	Canberra	Moree	Dubbo	Wagga Wagga
1972-92	71	120	104	116	92	81	97	101
1973-93	72	119	106	117	92	78	97	101
1974-94	72	119	106	116	92	78	96	101
1975-95	81	120	104	116	92	86	96	101
1976-96	81	119	104	115	92	117	109	101
1977-97	81	120	104	116	92	117	103	101
1978-98	81	112	104	116	98	116	106	102
1979-99	81	112	104	112	98	116	106	100
1980-00	81	114	102	109	98	116	106	100
1981-01	79	115	102	109	98	116	107	100
1982-02	104	114	102	114	98	113	107	100
1983-03	104	112	97	79	105	113	107	118
1984-04	117	111	99	79	104	112	107	118
1985-05	117	107	98	78	104	112	112	119
1986-06	117	106	95	80	105	112	112	124
1987-07	118	106	102	78	104	117	114	122
1988-08	118	105	104	105	106	117	114	122
1989-09	115	105	104	106	106	117	106	120
1990-10	114	93	104	113	113	120	111	125
1991-11	114	105	95	113	113	120	111	120
1992-12	114	93	92	113	113	120	111	125
1993-13	114	93	92	121	113	120	111	120
1994-14	114	101	120	120	114	128	110	120
1995-15	108	101	121	123	112	128	110	126
Mean	99	109	104	116	103	107	111	109
Overall	91	108	116	107	100	104	114	111
S.E.	3.40	4.56	3.62	3.41	3.69	3.67	4.12	3.15

It should also be noted that the regression equation for Coffs Harbour (and the other 7 stations assessed) has a high correlation coefficient (r^2=0.8647, see Appendix 15). It is apparent therefore that under the influence of historical climate change, there is an increase in the GEV_{50} since 1972 for most stations assessed, with Williamtown trending lower.

8.3.5 Summary of FFDI considerations.

To a large extent, the current study confirms previous computer simulated prediction (using GCM) for annual average ∑FFDI and numbers of days exceeding threshold values (notably FFDI$\geq$25), although this is not consistent. Past research using various GCM simulations for prediction may either under-estimate or over-estimate the changes when compared to the findings of the current study using historical data, although the results are of the same order.

From the assessment of annual and seasonal ∑FFDI, the changes in frequency of days exceeding threshold values of FFDI>25 and FFDI>50, the cumulative FFDI for days with FFDI>25 and the 20 year moving GEV_{50}, all indicate that, in general, there are changes in the frequency of fire weather events, seasonality shifts with rising FFDI, and increased severity of fire weather conditions at the extreme. The changes are not uniform across the NSW landscape, nor are changes of similar magnitudes.

The most consistent changes arising from the three metrics considered for FFDI indicate that the largest increases in fire weather can be found in western NSW, with higher elevations found in the Southern, Central and Northern Ranges and the New England showing mixed trends in relation to seasonal effects and numbers of days exceeding thresholds.

The northern coastal areas show some trend to lower severity in fire weather (using FFDI) which may be associated with more frequent rain events. Central and southern coastal areas all show some indications of increased fire weather under the influence of climate change.

8.4 Climate Change and FMC

8.4.1 Methods of analysis

To consider the impacts of climate change on FMC, a trend assessment was undertaken of FMC using the first two metrics described in Table 8.2. These metrics will be applied to all the 18 NSW sites described in section 8.2.1.

A rise in temperature and/or lower RH, will give rise to lower FMC values. Therefore, it should be anticipated that FMC will trend in the opposite direction to that of FFDI, assuming a hotter and drier climate.

Decreasing trends in FMC Metric 1 would indicate that fire weather frequency is likely to be increasing. For Metric 2 an increasing frequency of seasonal FMC falling below the threshold of 7% suggests that fire seasons are lengthening. Higher FMC for Metrics 1 and 2 may be associated with increased rainfall or changes in other weather parameters.

For trends at the extreme, the third metric of 20 year moving $GEV_{50}$for FMC was only applied to the 8 weather stations described in Table 8.1. A declining trend in FMC indicates increased severity of fire weather, or at least temperature and humidity as part of fire weather.

8.4.2 Changes in annual and seasonal ΣFMC

Table 8.8 provides a summary of annual and seasonal average ∑FMC over the period 1972-2009. Note that the values in this table are rounded to the nearest whole number.

The shifts in the 4 year progressive annual and seasonal ΣFMC were assessed for the 18 weather stations used in the current study.

Table 8.8: Summary of overall annual and seasonal average ∑FMC over the period 1972-2009

Weather Station	Overall Average Annual and Seasonal ∑FMC (1972-2009)				
	Autumn	Spring	Winter	Summer	Annual
	∑FMC	∑FMC	∑FMC	∑FMC	∑FMC
Grafton[a]	1080	845	831	1070	3826
Coffs Hbr	1211	1018	970	1178	4378
Williamtown	1139	911	847	1181	4078
Sydney	1126	914	859	1138	4038
Nowra	1136	934	876	1166	4113
Batemans Bay[a]	951	1086	1132	1010	4179
Cooma[a]	949	795	625	1172	3540
Canberra	960	827	618	1201	3606
Goulburn[a]	548	478	487	504	2017
Bathurst[a]	956	849	648	1251	3705
Armidale[a]	1013	836	763	1136	3749
Tamworth[a]	829	730	594	1061	3215
Moree	874	702	498	1171	3246
Coonamble[a]	844	691	566	1084	3185
Dubbo	895	739	555	1149	3339
Young[a]	871	810	533	1250	3464
Wagga Wagga	617	538	2301	2184	5641
Deniliquin[a]	923	832	663	1228	3647
a. data only for the period 1994-2009.					

Generally, ∑FMC is lower in spring and winter for weather stations when compared to summer, with the exception of Batemans Bay where spring and winter values exceed summer values. Wagga Wagga has the highest average annual ∑FMC, but has the second lowest spring annual average ∑FMC (after Bathurst). Goulburn has the lowest annual average (and seasonal) ∑FMC of all the stations.

Figure 8.5provides the results in 4 year moving annual and seasonal ∑FMC plots for the Grafton weather station, a near coastal location.

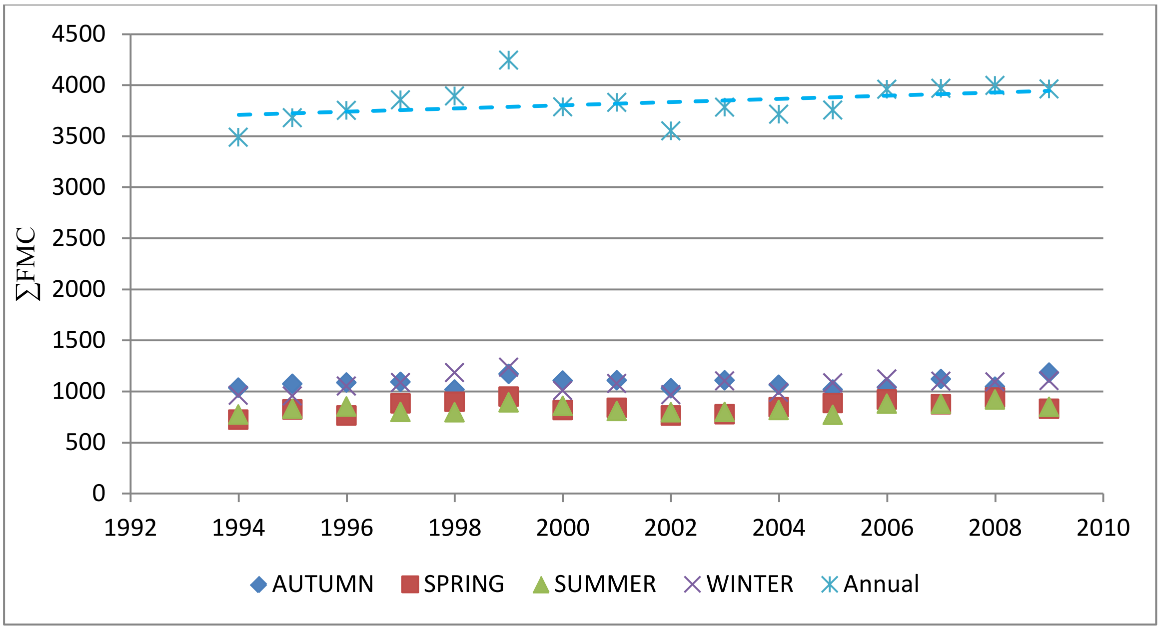


Figure 8.5: Annual and seasonal ∑FMC for Grafton weather station with annual regression line

As can be seen in Figure 8.5, the Grafton (Far North Coast) ∑FMC rises slightly over the period for both annual and all seasonal values, with some cyclic movement over the years. Low values for ∑FMC are associated with the years 1993-94 and 2002-03, the year's corresponding with ENSO events. As with FFDI, the use of progressive year plots for ∑FMC trends is not the only metric to be considered.

Figure 8.6 provides the results for the Tamworth weather station, which is in a Northern Tablelands location. A comparison between the above two weather stations illustrates how these results may present opposing trends for the same periods in different locations in northern NSW. The result for Tamworth is illustrative of the more common trend in ∑FMC for stations other than Grafton. Appendix 16 provides the detailed data and plots for all 18 NSW weather stations.

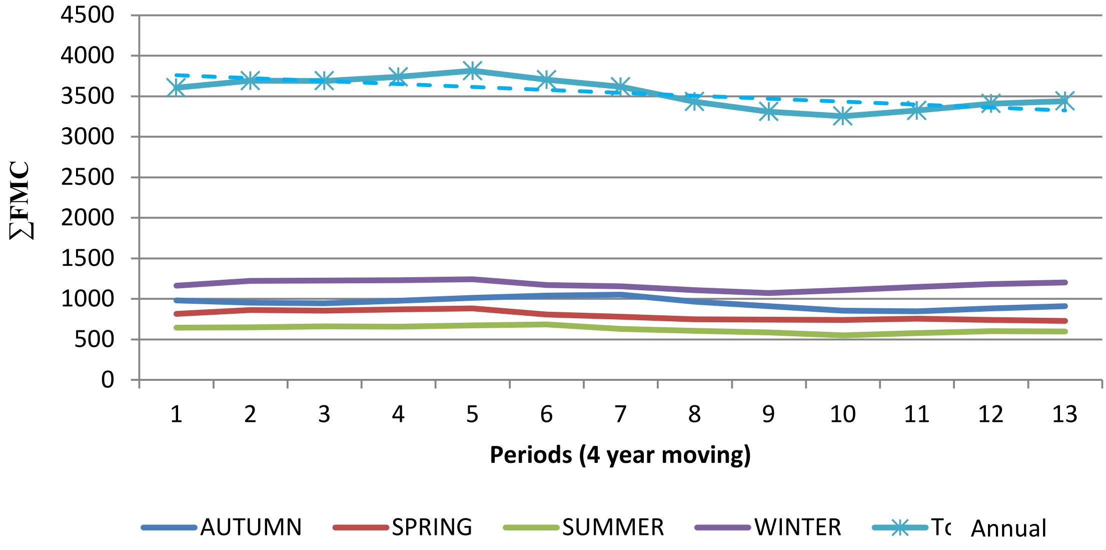


Figure 8.6: Annual and seasonal ∑FMC for Tamworth with regression line for annual results

Figure 8.6 shows that unlike Grafton, the Tamworth weather station demonstrates a declining regression line for the annual ∑FMC as well as all seasonal values.

Table 8.9 provides the slope (*S*) for the regression for the data on ΣFMC over the period 1972-2009. A negative value indicates lowering of ∑FMC for the period of the dataset.

Table 8.9 shows that, as with FFDI, ∑FMC is generally showing drying conditions over the period. The strongest effect for drying in spring is largely associated with the NSW Tablelands such as Cooma, Bathurst, Tamworth, Coonamble and Young. Weaker positive (wetter) trends are associated with Grafton, Sydney, Canberra and Goulburn particularly during the summer season. Deniliquin has a strong shift in positive trends during summer only.

Table 8.9: Summary of Trends (*S*) in annual and seasonal ∑FMC for 18 NSW fire weather station locations

Weather Station	Change in Average Annual and Seasonal ∑FMC (1972-2009)				
	Autumn	Spring	Winter	Summer	Annual
	S	*S*	*S*	*S*	*S*
Grafton[a]	+0. 173	+0. 567	+0.042	+0. 381	+1.564
Coffs Hbr	-0. 197	-0. 691	-0. 022	-0. 910	-0. 379
Williamtown	-1.162	-2.593	-2.477	-0.445	-6.677
Sydney	+0.170	-1.436	+0.462	+0.806	+0.002
Nowra	-2.485	-2.828	-1.220	+0.344	-6.189
Batemans Bay[a]	-1.412	-5.643	+2.511	-0.557	-5.100
Cooma[a]	-9.990	-26.559	-31.741	-19.729	-107.410
Canberra	-3.796	-1.838	-3.020	+0.332	-5.604
Goulburn[a]	+0.960	+1.932	+0.592	+0.564	+4.458
Bathurst[a]	-7.978	-11.808	-7.930	-0.8136	-28.530
Armidale[a]	-3.086	-2.606	-1.353	+1.124	-5.921
Tamworth[a]	-11.275	-12.172	-10.367	-7.693	-41.508
Moree	+1.950	-1.350	+1.417	+1.054	+12.121
Coonamble[a]	-14.381	-14.807	-10.840	-9.991	-50.018
Dubbo	-4.341	-2.138	-0.728	-0.877	-8.085
Young[a]	-10.631	-16.400	-2.979	-4.632	-34.639
Wagga Wagga	+0.472	+0.4875	+1.424	+1.864	+4.248
Deniliquin[a]	-2.469	-1.351	-9.832	+13.034	-0.618
a. data only for the period 1994-2009.					

8.4.3 Changes in the annual frequency of days below the threshold of 7%

As with FFDI, changes in the number of days in which the FMC falls below a critical threshold can also be used as a metric to illustrate the impacts of climate change on fire weather. Metric 2, or the 4-year moving average analysis is applied to FMC with the threshold of 7%. The use of the 7% threshold has been discussed in Chapter 4, (see also Luke and McArthur, 1978).This represents the critical value below which fire behaviour rapidly increases. Figures 8.7provides an example (Armidale) of the plot of data for number of days (annual and seasonal) at or below the threshold value of 7%.

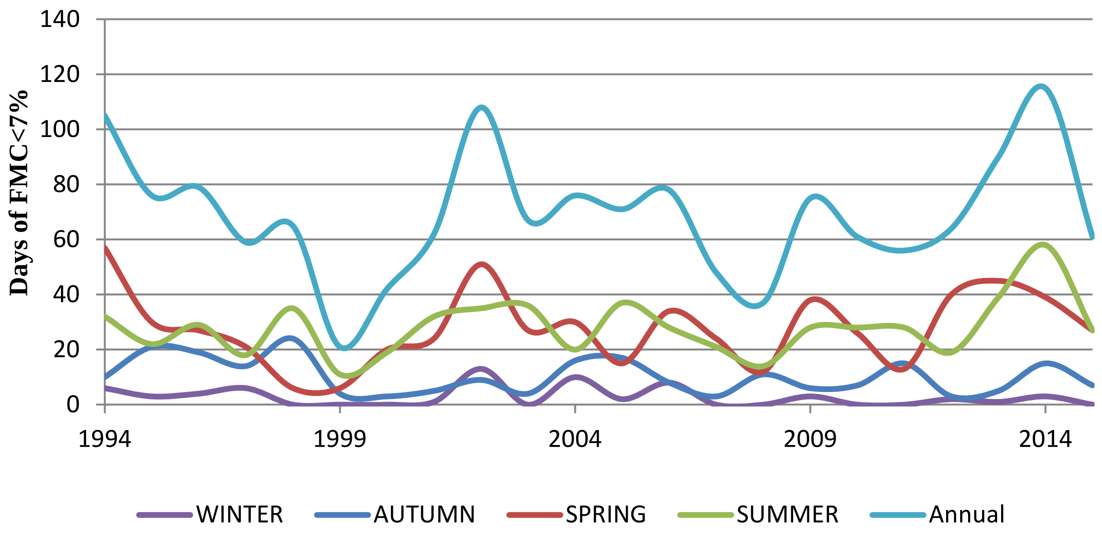


Figure 8.7 Frequency in the annual and seasonal no. of days exceeding the threshold of FMC ≤7% for Armidale

Figure 8.7 shows a slight rise in trend for number of days at or below the 7% FMC threshold. However, there is a cyclic pattern which largely corresponds to some extent with the ENSO years of 1994-5, 2002-3, and 2009. The highest number of days where FMC≤7% is recorded for Armidale are associated with recent years of 2013-14, being years with well above average temperatures.

The overall average annual and seasonal number of FMC ≤7% days for all 18 NSW weather stations are shown in Table 8.10.

As expected, winter has the lowest record of days when FMC is at or less than 7%.

In addition, western NSW weather stations (Moree, Dubbo, Coonamble, Young, Wagga Wagga, Tamworth and Deniliquin) all show higher annual number of FMC≤7% days. Although most of these are associated with summer, a large proportion of days (approximately 25%) are associated with both autumn and spring.

Table 8.10: Average annual and seasonal days at or below the threshold value of 7% FMC for 18 NSW weather stations for the period 1972-2015

Weather Station	Average No. of Annual and Seasonal FMC<7% days (1972-2015)				
	Autumn	Spring	Summer	Winter	Annual
Grafton[a]	2.0	14.3	23.0	5.5	44.7
Coffs Hbr	0.3	3.9	0.8	2.3	7.3
Williamtown	2.7	12.3	12.0	3.1	30.2
Sydney	4.0	13.8	7.8	4.1	29.7
Nowra	3.7	12.7	8.7	1.7	26.8
Batemans Bay[a]	2.7	8.2	4.2	1.5	16.5
Cooma[a]	12.2	19.2	32.1	4.0	67.5
Canberra	16.5	26.2	52.8	0.4	95.9
Goulburn[a]	15.6	25.9	46.4	1.2	89.1
Bathurst[a]	11.9	12.3	20.7	5.2	50.1
Armidale[a]	10.3	27.8	28.0	2.8	68.9
Tamworth[a]	31.2	47.2	62.0	5.2	145.6
Moree	34.7	51.6	74.5	8.1	168.7
Coonamble[a]	29.5	55.0	65.2	6.2	156.0
Dubbo	24.9	41.4	63.2	1.6	131.1
Young[a]	25.0	35.1	69.4	0.4	129.9
Wagga Wagga	27.2	33.1	72.8	0.2	133.3
Deniliquin[a]	26.7	47.6	75.0	1.1	150.5
a. data only for the period 1994-2015. All values rounded to one decimal place.					

The frequency of annual and seasonal FMC≤7% days for Deniliquin is shown in Figure 8.8.

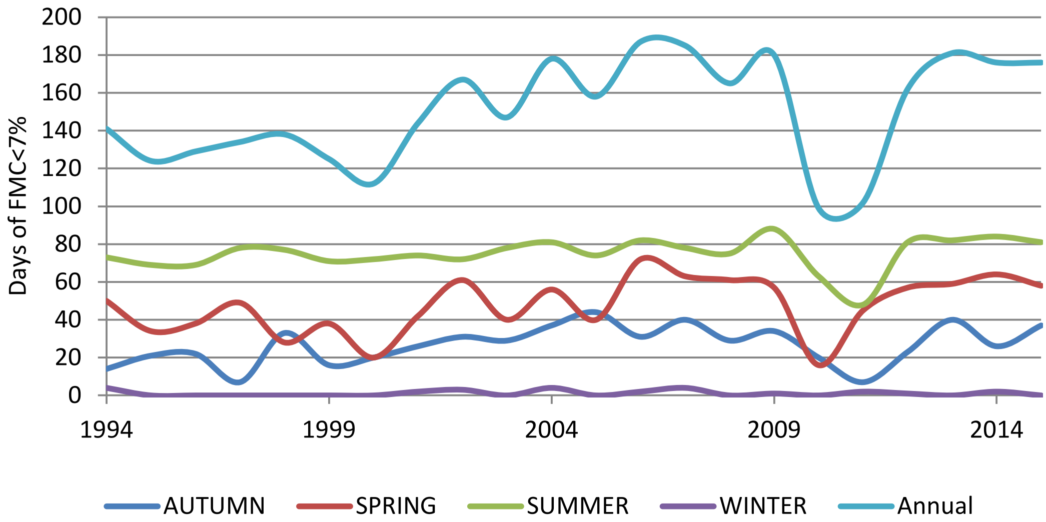


Figure 8.8: Frequency of annual and seasonal numbers of days of FMC ≤7% for Deniliquin

It can be seen that the onset of higher number of FMC≤7% days around 2010-2011 is preceded by the spring dip, followed by summer and then autumn at the end of the cycle. Interesting however, summer values are relatively flat except for the fall in 2011-2012. The period of 2010-2011 represents a drop- over most western NSW sites, and although a similar event is observed in coastal areas, the fluctuation is less pronounced.

There are no comparable studies for ∑FMC as those undertaken for ∑FFDI, or numbers of days at or below FMC thresholds as undertaken by Hennessey et al (2005) or Lucas et al (2007).

As such, the assessment of trends for FMC<7% days provides a new and innovative insight into fire weather considerations, notably when considering that FMC is a function of temperature and humidity.

The trends in 4 year progressive annual and seasonal number of FMC ≤7% days are summarised in Table 8.11.

Table 8.11: Trend in progressive 4 year annual and seasonal number days at or below 7% FMC for 18 NSW weather stations (1972-2015)

Weather Station	Trend in Frequency of Annual and Seasonal FMC<7% days (1972-2015)				
	Autumn	Spring	Summer	Winter	Annual
	S	*S*	*S*	*S*	*S*
Grafton[a]	0.91	-4.72	12.68	-1.78	5.27
Coffs Hbr	0.02	0.13	0.10	0.04	0.30
Williamtown	0.19	1.06	0.11	0.42	1.77
Sydney	0.07	0.58	-0.21	0.54	0.98
Nowra	0.04	0.63	-0.22	0.11	0.56
Batemans Bay[a]	0.08	-0.06	-0.50	0.01	-0.48
Cooma[a]	-1.76	1.53	-0.97	-0.16	-1.37
Canberra	0.10	1.51	-0.37	0.00	1.24
Goulburn[a]	-3.00	3.04	-2.78	-0.30	-3.04
Bathurst[a]	0.47	0.36	-2.94	2.71	-0.34
Armidale[a]	1.51	2.46	1.38	-0.53	1.80
Tamworth[a]	1.69	4.62	0.37	0.04	6.72
Moree	0.87	1.79	-0.88	-0.42	1.36
Coonamble[a]	-1.16	4.26	1.35	0.41	4.85
Dubbo	0.93	1.14	0.46	0.19	2.71
Young[a]	-3.59	3.87	-2.53	-0.17	-2.42
Wagga Wagga	0.20	0.67	0.22	0.01	1.07
Deniliquin[a]	1.80	4.20	0.30	0.14	6.45
a. data only for the period 1994-2015. All values rounded to two decimal places.					

From Table 8.11, it can be seen that winter trends are relatively flat, with a modest tendency in both the positive or negative direction, and independent of annual trend. Spring has a stronger trend than autumn overall, but that is not universal (see Grafton and Cooma especially). Summer and winter both have mixed trends in the positive and negative. At best, the trends in days with FMC $\leq$ 7% threshold are modest.

The slopes for all sites are significantly lower than the overall trends in threshold exceedance for FFDI (e.g. FFDI$\geq$25 or 50). Although the quantum of exceedance cannot be expected to be similar, some similarity in trend could be anticipated if FMC was a major driver of FFDI through climate change. This is not apparent, and it is surmised that as FFDI is also a function of wind and drought, the combined effect of these parameters are greater than that of temperature and humidity alone.

There is clear pattern of increases in ∑FMC and the number of days falling below the threshold of FMC$\leq$7%.It is likely, having regard to the differences in frequency for FFDI and FMC, that the use of the 7% threshold value for FMC may be too high.

Notwithstanding this, it can be seen that FMC is generally declining seasonally and annually, and that although winter is not showing any large trends in changes for FMC, trends only dominate in autumn, and are modest with large variations in summer and spring seasons.

As with FFDI, trends in ∑FMC and FMC<7% for the western areas are greater than that of the coast or ranges.

So as to consider the impact of FMC on fire weather severity, a GEV_{50} assessment for minimum FMC will be undertaken in section 8.4.4 below.

8.4.4 Changes in GEV_{50} for FMC

In section 8.2.3 above, the progressive GEV_{50} for FFDI was considered. This illustrated that notwithstanding some cyclic movement, FFDI appeared to reach new plateaus for recurrence levels. This suggests climate is shifting to higher fire weather conditions, rather than simply phasing through increasing cycles.

Figure 8.9 below, provides the plotted positions for the 20 year moving GEV_{50} of FMC at Canberra weather station. This shows a similar (albeit inverse) cyclic and plateau pattern for FMC as was seen in FFDI.

Only the 8 sites identified previously by Lucas et al (2007) have been used as these sites have 43.5 years of data whereas the NSW Fire Weather dataset has only 22 years and a progressive GEV cannot be undertaken. The results of the 20 year progressive GEV_{50} for FMC within differing periods for these 8 sites are given in Table 8.12 below.

Data has been corrected for season with starting dates of 1 June, 1972.

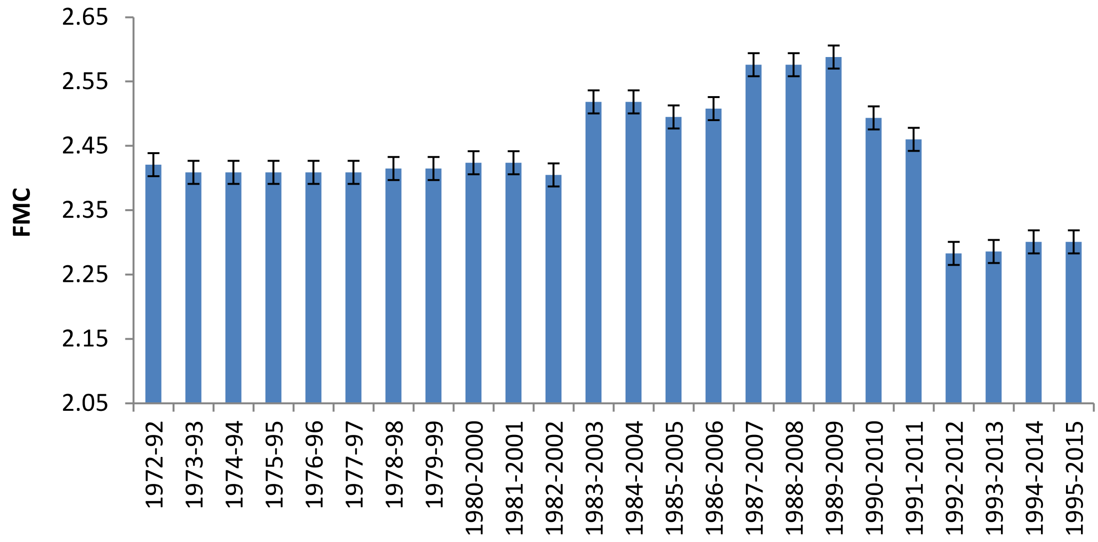


Figure 8.9: Moving GEV_{50} for FMC at Canberra Weather Station (1972-2015)

Figure 8.9 shows the cyclic and plateau forming nature of the GEV_{50} for FMC which is similar to that of FFDI, although for Canberra, the plateau is more pronounced in the last three years of analysis.

For FMC, it could be anticipated that there would be a decline in the GEV_{50} values over the 43.5 year period. Table 8.12 shows that for most stations, there is a decline in FMC over the 20 year progressive GEV_{50} recurrence level.

Table 8.12: 20 year moving GEV_{50} FMC values for 8 fire weather stations

Year	Coffs Hbr	Wil'town	Sydney	Nowra	Canberra	Moree	Dubbo	Wagga Wagga
1972-92	3.02	2.53	2.11	2.73	2.42	2.43	1.95	2.13
1973-93	3.02	2.53	2.21	2.72	2.41	2.41	1.95	2.13
1974-94	2.90	2.56	2.19	2.75	2.41	2.27	1.95	2.13
1975-95	2.76	2.56	2.19	2.75	2.41	2.11	1.95	2.16
1976-96	2.76	2.62	2.19	2.75	2.41	2.11	1.95	2.16
1977-97	2.78	2.62	2.15	2.78	2.41	2.12	1.95	2.16
1978-98	2.78	2.55	2.11	2.80	2.41	2.17	1.95	2.09
1979-99	2.81	2.55	2.11	2.72	2.41	2.14	1.94	2.09
1980-00	2.84	2.54	2.22	2.77	2.42	2.21	1.94	2.09
1981-01	2.84	2.52	2.17	2.78	2.42	2.17	2.27	2.09
1982-02	1.99	2.48	2.21	2.83	2.40	2.20	2.27	2.11
1983-03	2.03	2.28	2.45	2.66	2.52	2.27	2.53	2.15
1984-04	1.94	2.30	2.45	2.69	2.52	2.29	2.57	2.17
1985-05	1.86	2.31	2.54	2.68	2.49	2.30	2.61	2.20
1986-06	1.89	2.32	2.54	2.70	2.41	2.23	2.60	2.21
1987-07	1.96	2.36	2.51	2.55	2.58	2.25	2.55	2.25
1988-08	2.09	2.41	2.53	2.46	2.87	2.23	2.47	2.25
1989-09	2.08	2.41	2.50	2.51	2.59	2.24	2.47	2.25
1990-10	2.19	2.35	2.50	2.55	2.49	2.25	2.54	2.24
1991-11	2.22	2.35	2.49	2.55	2.46	2.25	2.54	2.24
1992-12	2.20	2.37	2.49	2.53	2.28	2.25	2.54	2.24
1993-13	2.20	2.41	2.56	2.53	2.29	2.26	2.54	2.25
1994-14	2.21	2.38	1.99	2.54	2.30	2.27	2.49	2.16
1995-15	2.17	2.38	1.99	2.54	2.30	2.31	2.49	2.07
Mean	2.40	2.44	2.31	2.66	2.44	2.24	2.29	2.17
Overall	2.56	2.45	2.16	2.49	2.43	2.32	1.95	2.17
S.E.	0.238	0.166	0.112	0.075	0.073	0.013	0.007	0.065

Dubbo and Wagga Wagga appear to have a rise in FMC over the period. This rise at Dubbo is quite pronounced relative to other stations. Dubbo is also the only station with a GEV_{50} recorded below the 2% minimum threshold used in this study. Dubbo therefore has a more consistent plateau across the whole dataset; however the rise is very small at 0.03%. The result for Dubbo, if corrected for a 2% minimum FMC, would have a lower rise, as the first 9 periods would all increase, lowering the trend line closer to zero. Clearly Dubbo s already at its limit in terms of FMC, and only the occurrence of rainfall in non-ENSO years would give rise to higher FMC than otherwise anticipated.

From these results, it cannot be clearly identified that either climate change or ENSO have a direct bearing on FMC using GEV_{50}, as the trends do not indicate major changes. Some effect is observed during the period 2001-2002 for some weather stations, notably Nowra and Wagga Wagga, but not in other stations.

As FMC is a function of temperature and humidity, the overall effect is modest for the GEV_{50} for FMC, with some increases observed in many of the 8 stations. Trends are much weaker than those observed in FFDI (section 8.2).

The results in Table 8.12suggest that the individual 20 year moving GEV_{50} assessments for FMC at all sites are near the 2% limits of FMC across all years (1972-2015). For coastal areas, the trend is more apparent, with trend to lower FMC being observed for the GEV_{50}.In particular, the overall GEV_{50} for FMC at Dubbo falls to 1.95%, a level which is not likely to be realistic, and reflects the earlier years of assessment.

The standard errors (S.E.) are very low indicating the closeness of the values at the extreme. The lowest value for S.E. is at Dubbo, where drought is more common, whereas the highest S.E. is at Coffs Harbour which is close to the coast and has a greater variability in rainfall.

8.4.5 Summary of FMC Considerations

The ∑FMC follows a similar pattern to ∑FFDI with decreases for most sites, and Grafton showing a rise in ∑FMC. However, there are more seasonal variations with FMC and Moree (inland site) and Goulburn (Ranges) also showing a rise in FMC.

Changes in the numbers of days less than the threshold value of FMC<7% is modest at best. as with ∑FMC, the overall trend is to lower FMCs at the coast and inland, with rises for the far north coast and at higher elevations.

The shift in GEV_{50} for FMC indicates a general decline in FMC at the *extreme*. Dubbo stands out as an exception, but FMC at this station is in many cases below the 2% values used as the minimum practical FMC that can be achieved, and biases the result more than for other sites.

8.5Drought (KBDI) and climate change

8.5.1 Methods of analysis

To consider the impacts of climate change on KBDI, a trend assessment was undertaken of KBDI using Metrics 1 and 2 described in Table 8.2. These metrics will be applied to the 18 NSW sites described in section 8.2.1 and Table 8.1.

The US Forest Service (Melton, 1989) considered that for a threshold above 150mm,heavier fuels would also contribute to fire intensity. It is also not anticipated that the maximum KBDI of 200 is achievable in reality and that levels of 180 are more likely as maximum values.

For Metric 2, the frequency exceedance threshold of KBDI at 150mm (i.e. KBDI>150) will be used.

A 20 year moving GEV50 assessment for KBDI was employed for Metric 3 and was undertaken for the 8 sites identified in Table 8.1.These sites have a longer dataset of 43.5 years. KBDI was found to have a succession of very high consecutive days and as such, is more clustered around a set of dates (notably in early 1983) than for FFDI or FMC. This will bias GEV as these dates will dominate successive years which utilise these same periods.

The Bureau of Meteorology regularly determine KBDI at weather stations and more regionally. The KBDI is effectively a complete dataset for both the National and NSW Historical Fire Weather Datasets.

8.5.2 Changes in Annual and Seasonal ∑KBDI

As with FFDI and FMC, KBDI can be considered in terms of the annual average and seasonal average of ∑KBDI. For consistency, the 4 year moving average will be employed to track the trends which may arise from climate change.

The determination of annual and seasonal average ∑KBDI was investigated for all 18 NSW sites used within the current study. Table 8.13 provides the summary of the overall annual and seasonal average ∑KBDI for the 18 NSW sites. Data was selected for the period 1972-2015 for the National Fire Weather, whereas for the NSW fire weather dataset, the period 1994-2015 was used.

As with FFDI and FMC, the annual cumulative values (∑KBDI) form an overall baseline of annual and seasonal values but do not of themselves suggest any trend in the time series data, or relationship with climate change.

Table 8.13: Annual and seasonal average ∑KBDI for 18 NSW weather stations

Weather Station	Overall Annual and Seasonal Average ∑KBDI (1972-2015)				
	Autumn	Spring	Winter	Summer	Annual
Grafton[a]	5388	8235	7076	6234	26932
Coffs Hbr	3945	7664	4792	6016	22416
Williamtown	4700	4569	1837	7206	18205
Sydney	4842	4640	2314	6896	18692
Nowra	5891	4454	3421	6942	20574
Batemans Bay[a]	4281	3094	2458	4184	14018
Cooma[a]	4034	1643	2386	3227	11290
Canberra	5152	1695	2456	4471	13657
Goulburn[a]	5339	1911	2845	4348	14442
Bathurst[a]	4707	1858	2469	3610	13237
Armidale[a]	2492	851	1398	1960	6701
Tamworth[a]	8529	4559	5900	6387	25375
Moree	10647	6105	7459	8751	32720
Coonamble[a]	9569	6691	6756	8812	31827
Dubbo	8064	3752	4291	7181	23104
Young[a]	8756	2379	3653	6876	21664
Wagga Wagga	8871	2475	3742	7313	22200
Deniliquin[a]	10048	5941	7505	8652	32146

a. data only for the period 1995-2015.

From Table 8.13, it can be seen that the western parts (notably Moree, Coonamble and Deniliquin) of the State have higher annual ∑KBDI values than that of the coast or tablelands. The lowest values for annual and seasonal average ∑KBDI is at Armidale.

Figure 8.10 shows the 4 year moving annual and seasonal average ∑KBDI for Sydney (Airport). It can be seen that an overall positive trend can be observed with KBDI for Sydney, consistent with that of FFDI in section 8.2.1.

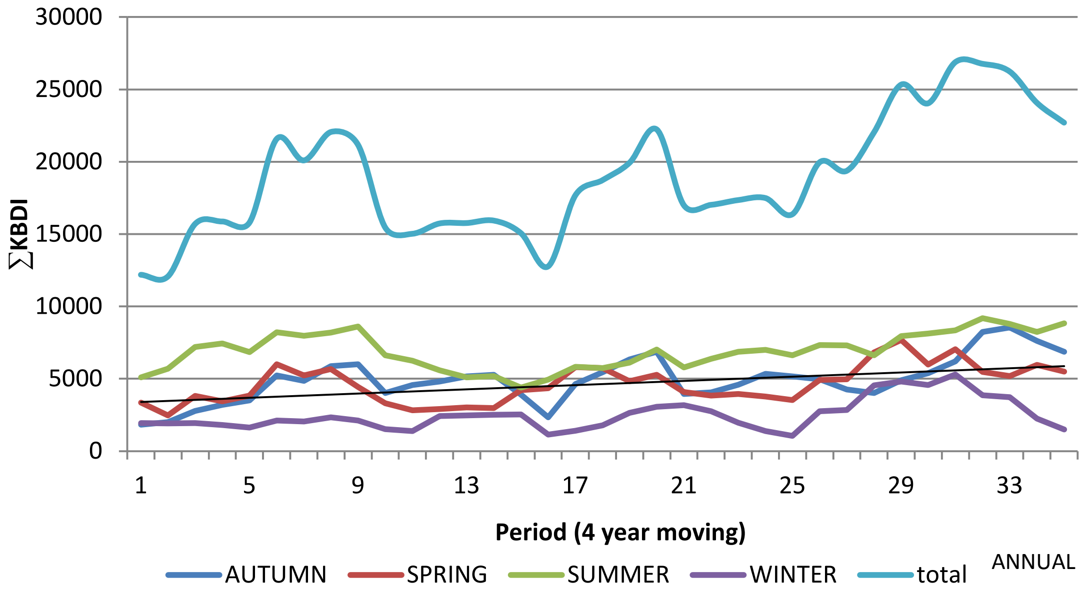


Figure 8.10: Trend in 4 year moving annual and seasonal average ∑KBDI for Sydney (Airport) weather station (1972-2009)

For Sydney, there is a cyclic movement in the results with the ENSO years, however with each cycle, there is a stronger KBDI during the summer, spring and autumn seasons. The winter season appears to return to non ENSO values with each cycle, however, the annual trend is consistent with a general rise in ∑KBDI.

The weather stations from the National fire weather database have positive trends (except for Coffs Harbour), as do many of the results from the NSW dataset. It maybe that the fewer years of data from the NSW dataset provides less certainty of outcome.

Table 8.14 shows the trend of the annual and season ∑KBDI values using the slope of the regression line. These values are taken directly from the data and do not include any moving averages.

Table 8.14: Changes (*S*) in 4 year moving annual and seasonal ∑KBDI for 18 NSW fire weather stations

Weather Station	**Change in Average Annual and Seasonal ∑KBDI (1972-2015)**				
	Autumn	Spring	Winter	Summer	Annual
	S	*S*	*S*	*S*	*S*
Grafton[a]	-101.9	-175.5	-186.1	-133.4	-597.0
Coffs Hbr	-6.39	-15.22	9.55	1.62	-10.42
Williamtown	-15.08	31.11	-22.86	10.0	7.62
Sydney	43.06	53.29	15.00	27.52	140.9
Nowra	78.75	62.62	33.66	19.01	196.1
Batemans Bay[a]	-82.41	5.69	-90.15	5.42	-161.5
Cooma[a]	-75.11	35.52	-24.33	44.59	-19.33
Canberra	71.44	24.86	47.73	1.37	145.4
Goulburn[a]	-220.5	58.63	-24.60	-92.02	-278.5
Bathurst[a]	-144.2	13.32	-101.9	-11.66	-237.6
Armidale[a]	1.22	22.87	30.05	8.49	62.64
Tamworth[a]	-173.0	62.37	-166.7	-94.21	-371.5
Moree	42.49	116.0	84.00	39.65	286.9
Coonamble[a]	-4.32	219.0	125.4	83.38	423.4
Dubbo	52.22	54.91	54.55	23.88	189.3
Young[a]	-243.1	70.09	-133.1	-41.54	-347.6
Wagga Wagga	7.87	55.03	35.18	12.76	116.3
Deniliquin[a]	-124.1	-157.8	-41.75	-3.85	-11.98
a. data only for the period 1994-2015.					

From Table 8.14 it can be seen that half of the weather stations have a positive trend with ∑KBDI over the data period. Grafton and Coffs Harbour have negative results for the coast, notably spring and autumn. Nearby Williamtown has a negative trend for autumn and winter, but positive trends for spring and summer.

The tableland areas of Cooma, Goulburn and Bathurst all have negative trends associated with autumn and winter, although the results for nearby Canberra (with its longer record) has a positive trend for all seasons. Armidale has a positive trend across all seasons, with the strongest trend associated with winter, followed by spring.

In contrast, Tamworth has a steep negative slope, with the exception of spring. Other western areas including Wagga Wagga, Dubbo, Moree and Coonamble exhibit positive trends, with the steepest being Coonamble.

The importance of this from a design bushfire perspective is therefore critical. The results of the KBDI analysis show that the Far North Coast (Grafton) and to a lesser degree the North Coast (Coffs Harbour) and Far South Coast (Batemans Bay) have negative trend in cumulative KBDI, whereas as the Greater Sydney (Sydney), Illawarra/South Coast (Nowra) and Canberra districts are all positive with time, and supportive of climate change as an underlying factor. Further inland, the results are mixed with the longer datasets all showing positive trends, whereas the shorter NSW Historical datasets, show a greater number of negative trends.

The overall results suggest a gradation of trends from north to south, generally increasing in positive trends, with a westerly trend towards increased drought (as expressed through KBDI).

A consideration of the 20 year moving GEV for KBDI should be able to ascertain, whether such trends are exhibited at the *extreme*.

8.5.3 Changes in the frequency of threshold exceedance

As with FFDI and FMC, Metric 2from Table 8.2 was used for KBDI. KBDI is a function of rainfall and temperature, and as such, can be an important measure of seasonal and annual changes in these weather parameters.

Figure 8.11 provides an example of a plot for the number of days exceeding the threshold of KBDI>150 for Canberra.

Table 8.15 provides an assessment of the number of days of KBDI $\geq$150 for the 8 weather stations identified in Table 8.1. The period of data is from 1973-2015.

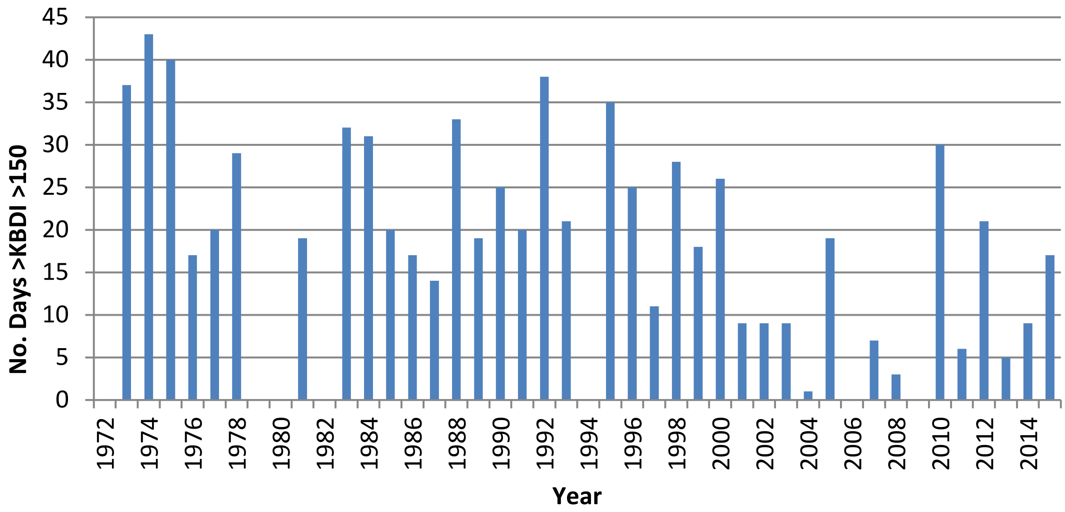


Figure 8.11: Canberra no. of days per year exceeding threshold of KBDI≥150

It can be seen for Canberra, the average of annual no. of days which exceed the threshold of KBDI>150 is trending down, with peaks in 1974, 1983-1994, 1996-2000, and 2010; largely corresponding to the onset of ENSO events.

Table 8.15: Average number of days per year (and trend *S*) and season exceeding the threshold KBDI≥150 for 8 NSW weather stations

Weather Station	**Average Annual and Seasonal No. of days KBDI>150 (1972-2015)**				
	Autumn	Spring	Summer	Winter	Annual (*S*)
Coffs Hbr	8.9	2.2	5.8	3.6	20.6 (+0.05)
Williamtown	6.5	2.5	2.0	8.5	19.3 (-0.05)
Sydney	5.8	2.8	2.6	7.2	18.3 (-0.19)
Nowra	4.3	3.7	2.7	4.6	15.2 (-0.36)
Canberra	1.4	7.4	1.7	5.8	16.4 (-0.43)
Moree	0.5	1.0	0.8	1.5	3.8 (-0.17)
Dubbo	1.0	3.5	1.4	3.8	9.6 (-0.15)
Wagga Wagga	1.1	6.1	0.9	8.4	16.5 (-0.36)
a. data only for the period 1994-2015. All values rounded to one decimal place.					

As can be seen from Table 8.15, the number of days exceeding the threshold value of KBDI>150 has reduced over the period, for the majority of weather stations. Even at a cursory level, it is apparent that the higher years of 1983 and for some stations the mid-1970s exhibited higher frequency of high KBDI number of days. However, the decline in number of days exceeding the threshold is not reflected in the rise in average KBDI over the same period (see Figures 8.6 and 8.7). The cumulative KBDI is rising but the threshold exceedance of KBDI>150 are associated with individual events, aligned more with the ENSO, than with the progressive rise that might be associated with climate change.

In effect, although individual ENSO events are associated with the most adverse fire weather conditions, the overall trend in KBDI is rising under the influence of climate change. In effect, if drought is considered as a pre-conditioning factor, then such a trend will be associated with the observed rise in the FFDI described earlier. This should therefore, also be reflected in changes to the GEV_{50} values for KBDI over period being investigated. These changes are considered in the next sub-section.

8.5.4 Changes in 50 year recurrence of GEV for KBDI

As with FFDI and FMC, the KBDI can be subjected to a GEV assessment, using the moving 20 year average approach. Table 8.16 provides the GEV_{50} results for KBDI for the 8 weather stations with sufficient data (i.e. 44 years). The periods used in Table 8.16 correspond to those in sections 8.2 and 8.3 respectively. The mean GEV_{50} of the 24 periods and overall GEV_{50} over the record are also determined.

As with FFDI and FMC, the only sites with sufficient number of years to employ the 20 year moving average method are those associated with the National Historical Fire Weather Dataset (see Table 8.1).

The moving GEV_{50}KBDI trend for the 20 year moving average is a positive one over time for most sites. For most sites, the mean (of 20 year moving) value is lower than the overall GEV_{50} results.

Williamtown, Sydney and Canberra all have declining KBDI GEV_{50} values. However, Canberra, is in effect quite static, with the GEV_{50} values for KBDI ranging from 161-158.

Table 8.16: Moving 20 year GEV_{50} KBDI values for 8 fire weather stations with mean and overall GEV_{50} values (1972-2015)

Years	Coffs Hbr	Williamtown	Sydney	Nowra	Canberra	Moree	Dubbo	Wagga Wagga
1972-92	171	182	176	177	161	187	174	180
1973-93	171	182	176	177	161	187	174	180
1974-94	171	182	176	177	161	187	174	180
1975-95	171	182	176	177	161	187	174	180
1976-96	171	182	176	189	161	187	174	180
1977-97	171	182	176	189	161	187	174	180
1978-98	170	182	176	189	160	187	174	180
1979-99	170	182	176	189	160	187	174	180
1980-00	171	182	176	189	160	187	174	180
1981-01	170	182	176	189	160	187	174	180
1982-02	177	182	176	189	160	187	174	180
1983-03	177	182	170	189	158	172	171	181
1984-04	175	182	170	189	158	189	171	181
1985-05	175	182	170	189	158	189	171	181
1986-06	175	182	170	189	158	189	172	181
1987-07	175	182	170	189	158	189	194	181
1988-08	175	182	170	189	158	189	194	181
1989-09	175	182	170	189	158	189	194	181
1990-10	175	182	170	189	158	189	194	181
1991-11	175	156	171	189	158	189	194	182
1992-12	175	156	171	189	158	189	194	183
1993-13	175	156	171	189	158	189	194	183
1994-14	175	156	171	189	158	188	194	183
1995-15	175	156	171	189	158	188	194	183
Mean	174	177	173	187	159	188	181	181
Overall	177	182	174	192	160	188	198	180
S.E.	0.304	0.271	0.801	0.689	0.303	0.208	0.430	0.126

Likewise, Wagga Wagga is also fairly static with results ranging from nearly 180 (179.5) to nearly 183. The trends in GEV_{50} results are usually associated with the stronger lag of results in the earlier periods, whereas other sites often had a more progressive and gradual shift.

The results for Wagga Wagga are illustrated in Figure 8.12 below. It should also be noted the low standard error associated with all sites, indicating how close the 20 data values used for the assessment are.

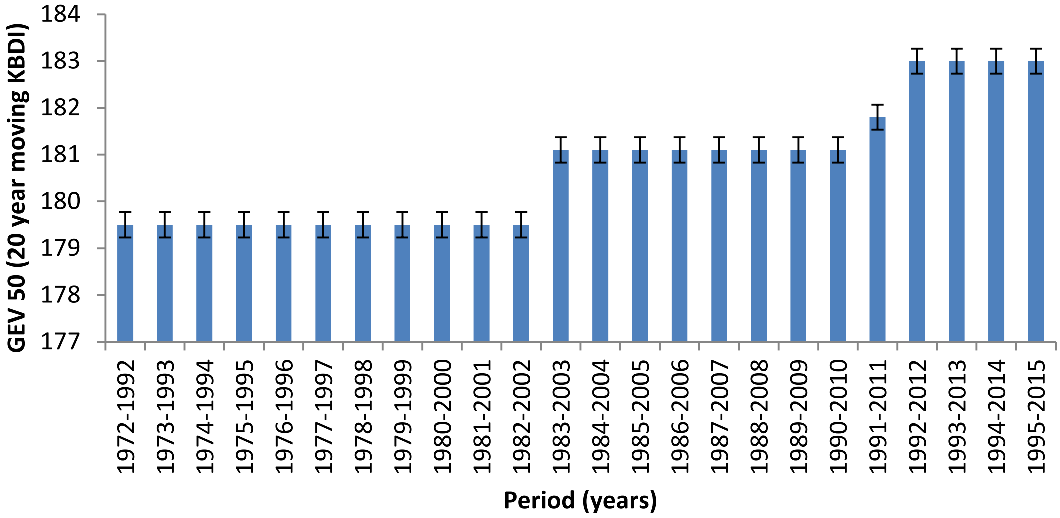


Figure 8.12: Results of the 20 year moving $GEV_{50}$for KBDI at Wagga Wagga (with S.E.)

Care needs to be exercised when considering the GEV_{50}values for KBDI. The higher number of consecutive high KBDI values in the dataset will give a persistent and repetitive GEV_{50} based on the same data points being used in the 20 year period. This was not observed for FFDI or FMC but was apparent for some sites, such as Wagga Wagga.

However, what is notable is that each site used for the GEV assessment, provided new plateaus or steps in the GEV_{50}. As with FMC, some care must be exercised where the KBDI exceeds 180, as a truly KBDI of 200 is considered unlikely, except in the semi-arid and arid zones. The result of KBDI of 197.8 for Dubbo, illustrates its importance of location on the edge of the semi-arid zone in NSW. Standard error for overall KBDI GEV indicates that the errors are all small and that the highest values are associated with Sydney and Nowra, with lowest values associated with inland areas. This again suggest variability in rainfall giving rise to the greater spread.

The shape parameters, intercept values and correlation coefficients (r^2) are provided in Appendix 16.

8.5.5 Summary of KBDI considerations

When considering drought, the changes in ∑KBDI show an increase in summer and spring seasonal values over the period, with ∑KBDI increasing at all sites, with the notable exception of Grafton. KBDI is highly variable for annual and autumn results, with winter being fairly negative to neutral. On an annual basis, there is a surprising number of declines in the number of days exceeding the threshold value of KBDI≥150. However, this is again highly variable with season.

For the GEV(50) analysis, KBDI shows a mixed pattern with Williamtown, Sydney and Canberra declining in KBDI, with other sites rising. Moree and Wagga Wagga show a relatively flat trend (only slightly increasing) which may reflect the limits of KBDI. Coffs harbour and Nowra have the largest increases in GEV(50) for KBDI.

8.6 ENSO and pattern of fire weather parameters

8.6.1 Methods of analysis

In addition to considering FFDI, FMC and KBDI, the trend on the corresponding SOI was also assessed. As discussed in Chapter 4, the overall trend for SOI is progressing to a slightly wetter conditions, however the regression provides a very low correlation coefficient (r^2=0.0011, α=0.002).

The role of SOI and IOD are discussed in Chapter 4 (see section 4.3).For the period of study (1972-2009) the SOI data was plotted so as to develop an overall trend for SOI. Where the inter-decadal trend is on the rise, then a wet period can be expected, and where the same trend is on the decline, more dry years can be anticipated (Speer, 2009).

The monthly data for SOI is shown in Figure 8.13 which was used to assess for inter-decadal trend. A 7 month moving average trend line was also plotted, so as to overlap with season and to show how SOI progressed over the years of study.

What can easily be discerned from Figure 8.13 are the major years of bushfire events, which correspond to strong negative SOI periods. Of particular interest are the years 1982-83 (Ash Wednesday – South Australia and Victoria), 1993-94 (Sydney fires), 2001-03 (Sydney and ACT fires), 2005 (Eyre Peninsular fires) and 2009 (Black Saturday – Victoria).

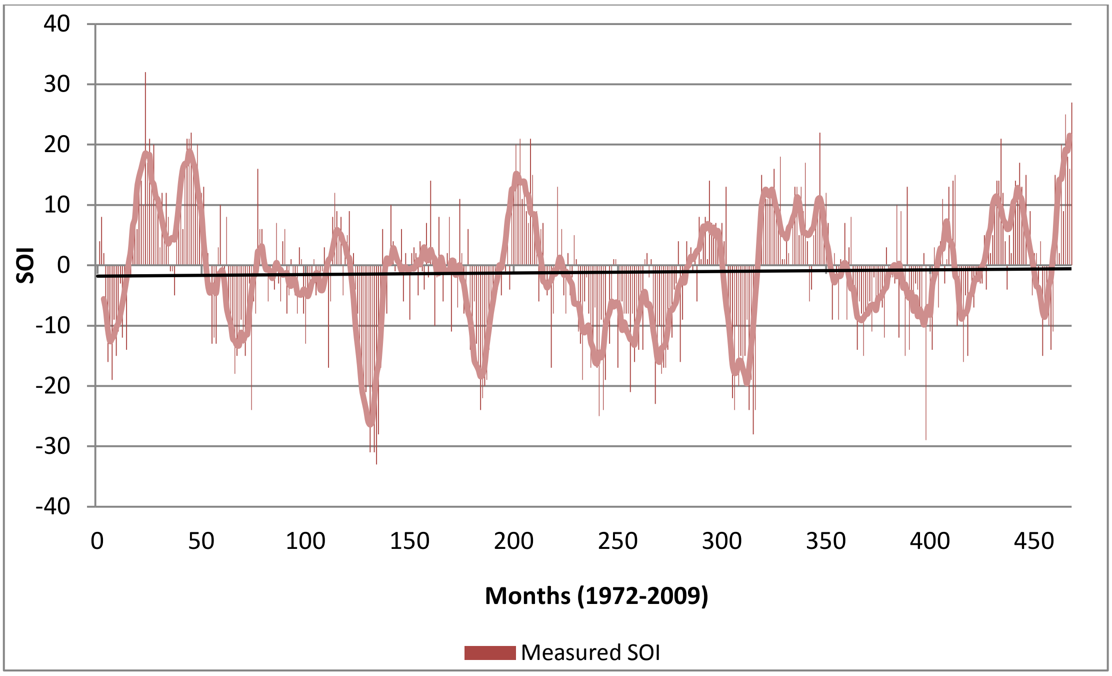


Figure 8.13: Southern Oscillation Index monthly data for the period 1972-2009 showing 7 year average trend line (red) and overall trend line (black)

As it was found that over the longer term record used, the trend was slightly positive, suggesting a gradual shift to wetter periods in Australia. If there is a relationship between ENSO and climate change, the trend to wetter conditions would be counter intuitive to that proposed by climate change investigations (Speer, 2009).

As identified in the previous sections, FFDI, FMC and KBDI exhibit some characteristics of drier conditions over most of NSW, although such trends are not uniform, nor are all metrics consistent in this indication (e.g. Grafton and ∑FFDI).

So as to test the relative relationship between the fire weather parameters (FFDI, FMC and KBDI) with SOI, a Pearson's Correlation was conducted between SOI and each fire weather parameter in turn for the 8 sites identified in Table 8.1. The results of this testing provides Metric 4 described in Table 8.2.

As a preliminary step, SOI was initially given a cumulative value for the bushfire season, designated ∑SOI. This provides an qualitative representation of the trends in SOI compared to each of the fire weather parameters studied, also summed for the bushfire season.

The second step was to apply the Pearson's correlation on monthly SOI with Monthly ∑FFDI, ∑FMC and ∑KBDI.

8.6.2 SOI and trends in bushfire season

Figure 8.14 provides a plot of ∑SOI values for the annual bushfire season (with reversed y-axis) which shows the major years in which SOI was strongest (i.e. more negative) are above the x-axis. A two year moving average trend line has also been included to illustrate the strength of previous drought years, in the lead up to major fire years. The year represents the bushfire season starting in October and finishing in March after.

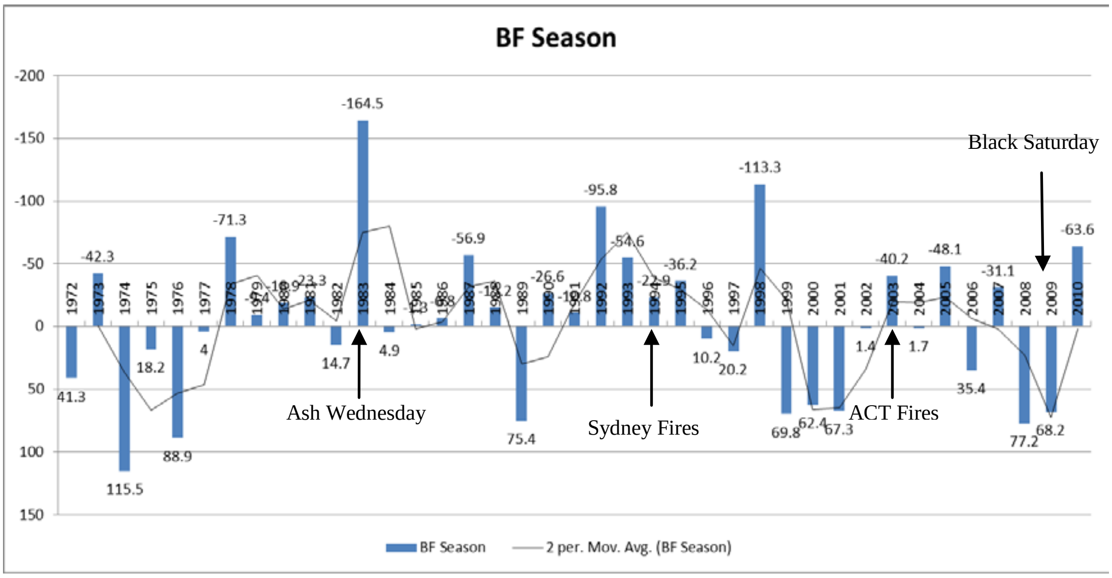


Figure 8.14: Annualised bushfire season (Oct-Mar) ∑SOI with 2 year moving average trend line

From Figure 8.13 and 8.14, the strongest ENSO years were confirmed as 1982-3, 1991-3, and 1997-8 with lesser rises in 2002-3, 2004-5 and 2009-10. Interestingly, the 2008-9 period, in which Black Saturday occurred, has an overall positive (or wetter) period than the following year. The strength of the bushfire season and monthly SOI does not correspond well with the cyclic nature of ∑FFDI discussed in section 8.2 above.

The presence of ENSO is an important aspect of global climatic conditions (as is the IOD). As such, a comparison can be made between SOI (adjusted for high negative values), FFDI, FMC and KBDI. A negative SOI would be expected to be associated with a lower FMC and higher KBDI and FFDI. A divergence between the plots of SOI and FFDI, FMC and KBDI suggests increasing (or decreasing) climate change effects whereas a mirror (or parallel) pattern indicates the influence of SOI on those parameters.

The current study uses a cumulative value for the bushfire danger period which runs from 1 October – 31 March in each year to compare ENSO with FFDI, FMC and KBDI. The 1972 year commences on 1 October 1972 and so on, concluding with March 2009.

Figures 8.15- 8.17provide plots of the sum of values for adjusted SOI, FFDI, FMC and KBDI for Sydney Airport weather station for the period from 1972-2010, which corresponds to the SOI data available.

For representation purposes, the SOI axis is shown in the primary (LH) y-axis position, with the FFDI (Figure 8.15) or KBDI (in Figure 8.17) shown on the secondary (RH) y-axis. For FMC the (LH) y-axis is used in Figure 8.16. In addition for presentation purposes the FMC is divided by a factor of 1 (/10) to better align the two sets of data and to adjust for scaling. As ENSO is a negative value, a reference to the term "Norm" in the legend of Figures 8.15-8.17 refers to normalised data by adjusting for the worst negative SOI value in the record. This provides a positive value for comparison with FFDI, FMC and KBDI. 1983 had the highest negative value (-164.5).

Figure 8.15 shows the pattern of ∑SOI and ∑FFDI as well as the associated regression lines.

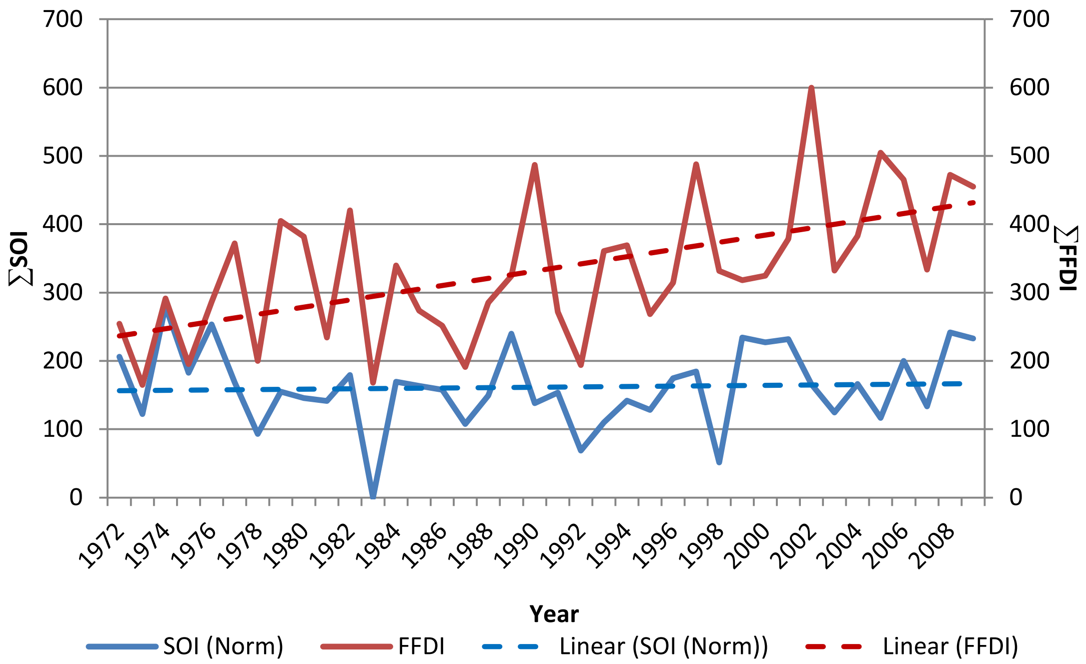


Figure 8.15: Comparison of ∑SOI vs ∑FFDI during the bushfire danger period (with linear regression lines) for Sydney

As anticipated Figure 8.15 shows the trend in SOI is relatively flat (weak rise in wetter conditions) whereas the FFDI value has a distinctive rise over the period (1972-2009).

In Figure 8.16, the plots show some similarity, although there are clear reverse troughs and peaks in 2000-2002 with the highest peak for FFDI in 2003. In addition, the plots progressively diverge from each other over the period of data.

This is also seen in Figures 8.16 and 8.17 below for FMC and KBDI respectively. In Figure 8.16, FMC declines over the period 1972-2009.

For Sydney, there appears to be a clear divergence in relation to FFDI, FMC and KBDI when compared to SOI.,

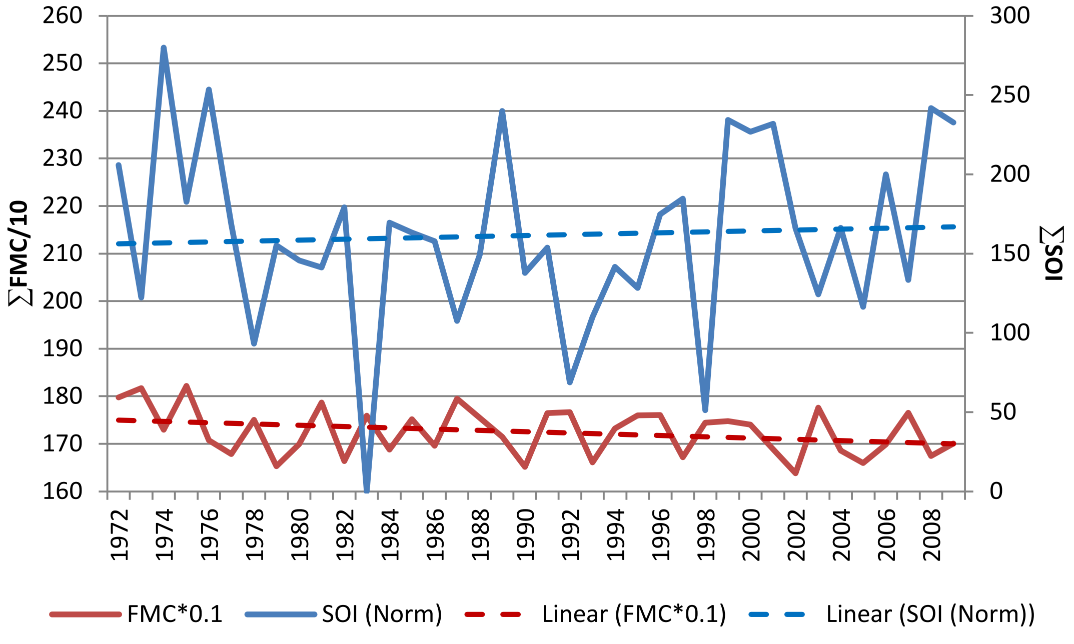


Figure 8. 16: Comparison of ∑SOI vs ∑FMC (/10) during the bushfire danger period (with regression lines) for Sydney

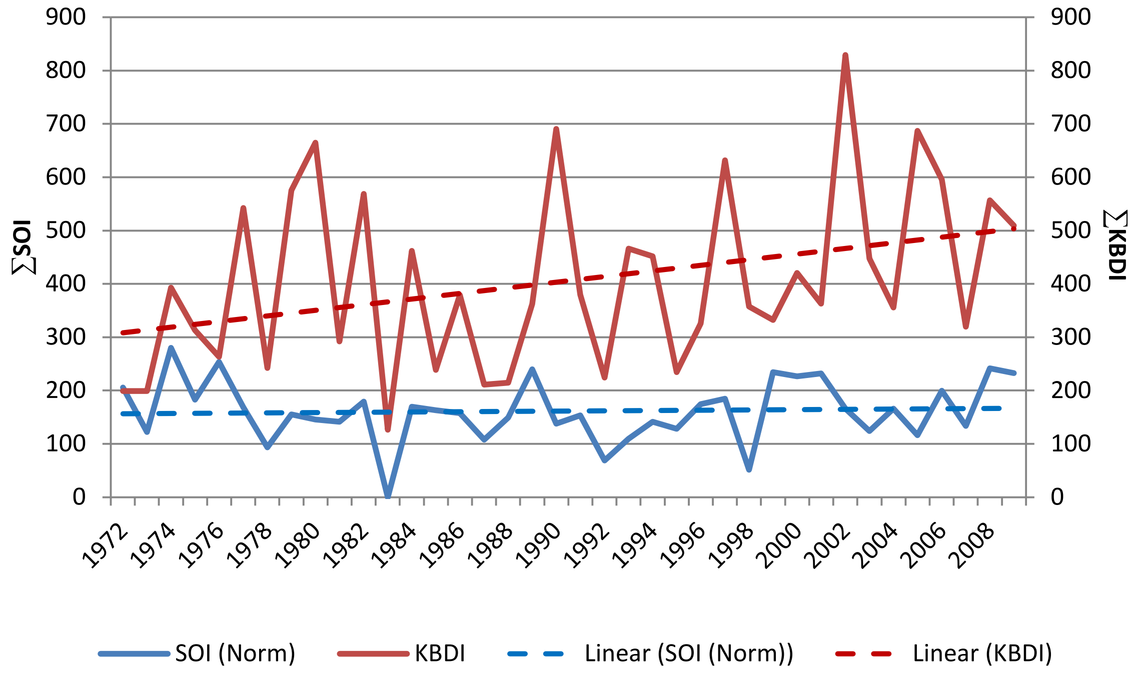


Figure 8.17Comparison of ∑SOI vs ∑KBDI during the bushfire danger period (with regression lines) for Sydney

From the representation in Figures 8.15 - 8.17, there is a small shift in SOI towards positive, which is anticipated. In the case of FFDI, FMC and KBDI there are clear patterns of divergence observed when compared with SOI. Of itself, this is not an adequate method for considering SOI association with fire weather and requires quantification.

A Pearson Correlation was therefore undertaken and is described in the sub-section below.

8.6.3 Correlation between monthly SOI and ∑FFDI, ∑FMC and ∑KBDI

Where SOI is a confounding factor in trends in fire weather associated with climate change, then the correlation should be positive and high. If shifts in climate is not associated with ENSO, then it can be expected that correlation would be negative and/or have lower values for FFDI and KBDI. For FMC the same would be apparent, however, positive rather than negative values may apply.

A process of simple correlation between monthly SOI and a monthly cumulative value for FFDI, FMC and KBDI was undertaken for each of the 8 sites with data ranging from 1972-2009.

Table 8.18 provides a summary of the Pearson Correlation Coefficients (*r*) results for this analysis.

Table 8.17Pearson Correlation (*r*) for monthly SOI with monthly ∑FFDI, ∑FMC and ∑KBDI (1972-2009)

Weather Station	SOI *v* ∑FFDI	SOI *v* ∑FMC	SOI *v* ∑KBDI
Coffs Harbour	-0.0989	-0.0105	-0.1322
Williamtown	-0.1153	0.0146	-0.1237
Sydney	-0.1028	-0.0043	-0.1448
Nowra	-0.1574	0.0397	-0.1850
Canberra	-0.2319	0.0704	-0.3134
Moree	-0.0764	-0.0231	-0.3390
Dubbo	-0.2057	0.0962	-0.3363
Wagga Wagga	-0.1474	-0.0727	-0.2617

From Table 8.18, it is apparent that correlations are low, with *r* values being less than 0.35 and the majority of the results being negatively correlated. For monthly ∑FMC, some sites (Williamtown, Nowra, Canberra and Dubbo) were positively correlated, but for *r* values of less than 0.1.

From this assessment, it can be concluded, based on the data available, that there is little correlation between SOI and fire weather consideration associated with climate change. This is not to say that the onset of an ENSO event does not lead to increased fire severity over the short term. ENSO events do not appear to be major determinants in the long term (climate) changes associated with changes in fire season, changes in the frequency of higher fire weather or changes in the severity of fire weather.

8.7 Summary

In this Chapter, an analysis has been undertaken of trends in FFDI, FMC, KBDI and SOI and the likely implications arising from global climatic events (ENSO) and climate change. Due to its improved sensitivity for assessment, cumulative values have been used rather than means, and the use of 4 year moving averages for these cumulative values assists with smoothing out larger fluctuations in weather.

Importantly, the current study has extended previous research on observations arising from the Bureau of Meteorology datasets. In addition, comparable metrics in terms of FMC and KBDI have also been considered based on the concept of moving average, as well as the use of the predicted 50 year recurrence values from the GEV analysis.

The current investigations have provided significant improvements on previous investigations of this type (namely Hennessey et al, 2005 and Lucas et al, 2007). These improvements include:

1. datasets used in the current study are wider in coverage with more NSW weather stations providing representation of all the NSW fire weather districts (with forested vegetation classes) and covering a longer period of time;
2. new methods through the use of new metrics which have been introduced, including the use of the GEV assessment approach through a moving period approach;
3. the metrics being applied to not only FFDI, but also to FMC and KBDI; and
4. the resultant trends in fire weather parameters have been considered in conjunction with SOI.

The present study has found that for most metrics, there appears to be a trend to deteriorating fire weather, as measured by FFDI, FMC and KBDI. That is, fire weather activity (frequency), seasonality and severity are increasing. FFDI is a function of drought (rainfall), temperature, humidity and wind speed. Fuel moisture (FMC) is a function of temperature and humidity, and as a measure of potential fire behaviour, shows a similar trend to more frequent lower fuel moisture days. Likewise drought (as measured through KBDI) provides a useful measure of the relative influences of drought which may be associated with global events.

Overall, the SOI (and IOD) plays an important part in fire weather. What has not been previously considered however is that the cyclic SOI events do not provide a sufficient explanation for the increasing trend to drier and more fire prone conditions in NSW.

From the current investigations, years subject to strong seasonal ENSO events, have the most adverse fire seasons, however, the overall trend for drought is increasing, leading to greater influences on pre-conditioning effects associated with drying conditions. This leads to the stepped increases in FFDI and KBDI observed for GEV_{50} assessments. However, the overall trend is neither uniform nor is it consistent across all weather districts.

For the northern coastal areas, notably Grafton, Coffs Harbour and Williamtown, there are some indications that wetter conditions may be prevailing, whereas other areas are exhibiting trends to drier and hotter conditions. This is not to suggest that climate change is not a factor, but rather that climate change can result in either wetter or drier conditions depending on districts as well as seasons. To some extent, the current study has added to the quantification of current and future risk arising from BoM data which indicates changes in Tmax and rainfall (see Chapter 1).

The period of the fire season also appears to be expanding, with the spring and autumn periods (as well as winter) showing increased number of days per annum associated with fire weather conditions (i.e. FFDI$\geq$25). Some of these seasonal aspects can vary dramatically across the landscape.

When compared to the use of GCM for simulation of trends in frequency of days and seasonal shifts to fire weather arising from climate change, the current study provides some support for these models. Notwithstanding this, care must still be exercised when using such models, as there are likely to be uncertainties and bias associated with such approaches. Drought, as expressed through KBDI, is rising for coastal areas, but appears to be at maximal conditions over most years farther inland.

The use of the GEV (at the 50 year recurrence) has been a useful addition to considering the implications of climate change on land use planning and construction practice for bushfire protection. This provides a useful and quantitative measure of changes in the severity of bushfire events over time.

The trends strongly suggest that with changes in global climate, that NSW is particularly susceptible to increasing frequency and severity of fire weather at the *extreme*. This will be most apparent at the coast and tablelands, whereas the drier western areas show already prevailing higher adverse fire weather conditions.

CHAPTER 9 - SUMMARY AND CONCLUSION.

9.1 Overview

Climate change is a statistical shift in the long-term patterns of weather, including temperature, rainfall and other weather parameters. Climate change is almost certain to have given rise to increased frequency of severe drought in south-east Australia and as such, increased frequency and prolonged period of adverse bushfire conditions. Although there is some evidence of these impacts which have extended the fire season from summer dominated to an increasingly stronger spring and autumn fire season in south-east Australia, it was not clear if the effect that climate change has had, was on the severity of bushfire events.

As discussed in Chapter 1, it is not the intention of this study to prove or disprove climate changes arising from anthropogenic or other causes, but to consider what are the implications for adaptation polices that may be necessary arising from the impacts of climate change.

Until the current study, no comprehensive and rigorous investigation has been undertaken, to derive the necessary conditions for either land use planning or construction practice under static, let alone dynamic environmental conditions, associated with bushfire events. Previous attempts at developing the 'design bushfire' have suffered from a lack of adequate data, inappropriate methodology and lack of statistical robustness. The use of CGM (or regional variants) when compared to historical data have a tendency to under-estimate recurrence due to the complex nature of FFDI and different periods over which maximal values may occur in the landscape.

9.2 Forest Fire Behaviour Models

It is of considerable importance for land-use planning and construction practice to have suitable bushfire design conditions, which is contingent on suitable climatic and fuel descriptors as well as bushfire behaviour models.

For forest (and grassy woodlands), two empirical fire behaviour models (FFDM5 and DEFFM) were used for comparative purposes, and to develop separation distances based on land-use and construction practice. FFDI and FMC are derived climatic parameters for use in such models. FFDI has been a long standing parameter, utilised within the FFDM5 model. FMC is used by the DEFFM approach.

In addition to climatic conditions, these two models differ markedly in relation to fuel input conditions. The FFDM5 uses a fuel load (t/Ha) assessment, whereas the DEFFM model relies on a system of structural hazard scores and fuel heights for vegetation.

It was found that while the rates of spread showed that the DEFFM was three or more times faster than for the equivalent FFDM5 values, that flame heights were of the same order between the two models, and that these flame heights were not always higher for DEFFM when compared to FFDM5 for the same vegetation classes.

Other models used for forests (in WA), grasslands, mallee-heath, and shrublands, have also been identified. Although these fall outside the scope of the current study, the methodological approach undertaken in the current study can be applied to these fire behaviour models, as applied to forests and woodlands.

9.3 Vegetation Formations, Classes and Fuel Assessment

The current study has compiled an improved fuel characterisation for NSW forest and grassy woodland formations. The study has identified that 18 of the 21 fire weather districts in NSW exhibit vegetation classes within these formations. Of these formations, the WSFs are largely confined to the coastal and tableland districts of the State. DSF are found more broadly across the landscape and extend from the coast to the central and western plains. Grassy woodlands are likewise found broadly within the landscape, with a greater presence in the alpine and western districts of the NSW. Approximately a third of the state (i.e. far west) has little to no significant extant forest or grassy woodland vegetation classes.

Five (5) of the formations/sub-formations described in this study are suitable for comparative purposes (Watson, 2013), these being:

- Wet sclerophyll forests (shrubby) sub-formation (7 classes);
- Wet sclerophyll forests (grassy) sub-formation (2 classes);
- Dry sclerophyll forests (shrubby) sub-formation (14 classes);
- Dry sclerophyll forests (grass/shrub) sub-formation (11 classes); and

- Grassy woodlands formation (7 classes).

The NSW forest and grassy woodland vegetation classes have been assessed using both fuel load and hazard score characteristics, however, there is limited data on fuel height characteristics for all forest and woodland formations. it was found that 9 vegetation classes can be used to develop a surrogate set of vegetation classes which comprise 2 WSF (one each of grassy and shrubby sub-formations), 6 DSFs (comprising grassy shrubby and shrubby sub-formations) and one grassy woodland.

This has allowed for the use of the two forest fire behaviour models to determine rates of spread and flame heights at the *extreme* using the GEV_{50} approach, for benchmark regionalisation of design bushfires in each of the NSW fire weather districts with forest and woodland vegetation classes.

9.4 Climate and Fire Weather under Climate Change

The role of climate can be considered in terms of frequency of environmental conditions, seasonality changes, as well as recurrence of *extreme* events in developing the bushfire scenarios for future planning and adaptation strategies.

FFDI is a function of drought (rainfall), temperature, humidity and wind speed. Fuel moisture (FMC) is a function of temperature and humidity and shows a similar trend to decreasing fuel moisture days. Likewise drought (as measured through KBDI) provides a useful measure of the relative influences of the SOI and climate change.

Preliminary metrics have been previously developed for FFDI from previous studies, which can also be applied to FMC and KBDI. However, the role of *extreme* value assessments should also form a part of the suite of metrics in developing design bushfire conditions.

9.5 Data and Methodology

A more comprehensive fire weather dataset has also been developed. Previous datasets developed by Lucas (2010) have been extended to ensure coverage of at least one representative weather station for each of the 21 NSW (and ACT) fire weather districts. Some data, within these meteorological datasets, are comprehensive, such as KBDI, rainfall and daily maximum temperature. Other parameters, such as wind speed and humidity are less comprehensive, and give rise to some uncertainties, necessitating test data and gap filling.

To address both design bushfire conditions, as well as consider the shifts in the design bushfire arising from climate change, this study uses the principles of extreme value assessments at the 1:50 recurrence level.

Three different EVA methods were utilised with the available fire weather data to determine *extremes* of fire weather conditions. The methods tested were the traditional Gumbel method (Amax), Generalised Pareto (GPD) and Generalised Extreme Value (GEV) distributions. It was found that the GEV performed best both for tests of significance and for correlation coefficients. A minimum of 20 years of data, was found to be necessary to provide a suitable basis for assessment. However, to ascertain the implications for climate change, a much longer period, in the order of 40 plus years, is necessary to consider the dynamic nature of climate change within the landscape.

The three *extreme* value assessments (GEV, GPD and Amax) were applied to fire weather conditions, fuel moisture and KBDI. FFDI, fuel moisture, wind speed, maximum temperature, relativity humidity and KBDI conditions; and can all be modelled within the theory of *extremes*.

Overall, among the three extreme value assessments methods, GEV method provides the best fit of data and best correlation coefficients for FFDI, FMC and KBDI. This also provides for the simplest assessment process of the three approaches.

Other metrics have been developed, including the use of cumulative annual and seasonal parameters (for changes associated with fire season) and frequency in exceedance of threshold value (for fire frequency).

Pearson correlation coefficients have also been used to determine if other global climatic factors, notably the SOI, has had any impact on the shifts in the above metrics, rather than being associated with climate change.

9.6 Synthesis of Results for Land-Use and Construction Practice

The assessment of dominant wind directions confirms previous studies from Victoria, that in NSW, the most likely winds associated with EXTREME bushfire conditions are from the north, north-west and west. Wind speeds for most sites exceed the policy setting of 45kph used in calculating fire behaviour for grasslands or heaths, and as applied within the DEFFM forest fire behaviour conditions.

Fuel moisture (FMC) was also assessed for its 1:50 year return period. In some cases, the resultant fuel moisture content fell below the limiting value of 2% FMC. Most FMC_{50}values lie within the 2-3% range and none exceeds 3.55%. Similar assessments of KBDI, show that drought is a consistent factor in fire weather considerations. KBDIs at the *extreme* end of the range can approach or exceed 180mm, which is also approaching the limit of 200mm.

The advantages of the GEV model is that it can be applied to the outputs of the two forest fire behaviour models, that is, rates of spread and flame height. The challenges arise when applying the log-linear GEV recurrence model to either intermediate or input parameters. In the case of FFDI, there is a direct relationship between the intermediate parameter and the output, whereas for the DEFFM model, the outputs are dependent on the two intermediate parameters of FMC and wind speed.

The study confirmed that it would not be appropriate to apply *extreme* value techniques on inputs or intermediary parameters, as this would lead to excessively conservative outcomes.

It is apparent, without taking climate change into account, that the coastal and tableland areas of NSW share similar fire weather conditions and fire behaviour, and as such, planning policy and construction practice needs to be amended to address any deficiency in those districts which currently do not have adequate protection.

The current investigations have provided significant improvements on previous investigations of this type. The application of GEV is robust and can be applied for either fire weather or for the design bushfire.

9.7 Implications of Climate Change on Fire Weather

Four metrics were introduced in the current study for assessing the impact of climate change on fire weather conditions or parameters within the State of New South Wales. It has been found that for most metrics, there appears to be a trend to deteriorating fire weather, as measured by FFDI, FMC and KBDI.

In general, there was a corresponding positive change in frequency of threshold values for FFDI($\geq$25 or $\geq$50), FMC ($\leq$7%) and KBDI ($\geq$150). Cumulative annual and seasonal fire weather conditions (exhibited through $\sum$FFDI, $\sum$FMC and $\sum$KBDI) also displayed shifts arising from climate change, although again this was not uniform over all districts.

The moving 20 year GEV_{50} shows a trend to more severe fire weather conditions, however the changes range from subtle to pronounced. These results have implications for adaptation in future land use decision making.

For the northern coastal areas, notably Grafton and Williamtown, there are some indications that wetter conditions may be prevailing over time. This is not to suggest that climate change is not a factor, as climate change can results in either wetter or drier conditions. For other areas, drier conditions are occurring with time, with some areas in the central west at the extreme ends of their range.

The period of the fire season also appears to be expanding, with the spring and autumn periods (as well as winter) showing increased periods associated with increased fire weather conditions. Some of these seasonal aspects can vary dramatically across the landscape. These shifts are often subtle with only small changes in fire weather parameters for some districts.

The use of Extreme Value Assessments, notably GEV, has allowed for the assessment of changes in fire weather severity. Through the use of GEV, it has also been possible to ascertain how ENSO as a global factor, has impacted on *extreme* fire weather events. ENSO was not found to play a significant role in changes in climatic fire weather parameters at the *extreme* which is used for the design bushfire in NSW.

The trends strongly suggest that with changes in global climate, that NSW is particularly susceptible to changes in frequency and severity of fire weather at the *extreme*. This will be most apparent at the coast and tablelands, whereas as the drier western areas already show prevailing higher adverse fire weather conditions.

However, the trends are neither uniform, nor are all sites trending in the same direction, with the north coast of NSW exhibiting wetter conditions over the period, and increasingly adverse weather conditions further south. This variation requires the management of fire weather conditions to be correspondingly variable, having regard to the conditions of the region and even more locally. With additional historical weather data availability, it should be possible to better target developments in bushfire prone areas to the conditions of a locality. Likewise, increasing information on local vegetation at the class level, can better target developments over time.

9.8 Concluding Comments

The major contributions of the current study have been fourfold, these being:

1. A more rigorous scientific foundation has been developed and employed for policy setting in bushfire protection;
2. A new methodology has been developed for the assessment of shifts in the severity of fire weather arising from climate change;
3. The study has provided a detailed mapping of risk in terms of recurrence of fire weather parameters across all 21 NSW Fire Weather Districts; and
4. Providing guidance for bushfire design practice, including the further application and refinement of a robust methodology to improve relevant standards, tools for assessment, and scenario development.

In summary, the GEV analysis has provided a simple and powerful tool for considering the implications of climate change on land use planning and construction practice for bushfire protection. Although the 50 year recurrence predictions have been used as the benchmark for analysis in the current study, the incorporation of any other recurrence periods is straightforward should they be selected for future policy making to face the challenge of adaptation to climate change.

9.9 Future Research

As a result of the investigations undertaken within the current study, a number of key limitations have been identified. These limitations arise from the absence of data or from the scope of the present study.

The use of surrogate vegetation classes has provided a sound basis for comparative assessments; however, these vegetation classes do not represent all forest and grassy woodland vegetation classes. Additional work on the grassy woodlands, particularly those associated with alpine and far west of NSW is warranted as the current fuel assessments are likely to underestimate fire behaviour outcomes. A more comprehensive assessment of fuel characterisation for NSW forests and woodlands is warranted, so as to build up an improved dataset of these conditions.

The investigations discussed within this study has been limited to the simplest of scenarios. The scenarios assume flat terrain and is limited to surrogate vegetation classes.

Wind has only been assessed largely in terms of dominant wind direction, during more SEVERE-EXTREME fire weather conditions. The current study shows that although wind speeds are higher than that currently adopted for determining the design bushfire, wind speed data is limited with major data gaps being prevalent.

The GEV approach can be applied to other fire behaviour models, notably those associated with native grasslands and shrublands (including mallee-heath). It can also be applied on a seasonal basis, to better quantify changes arising from climate change. From a land-use planning and construction practice perspective, the current study has illustrated that current policy settings for wind speed and fuel moisture, may well be under-estimating risk associated with these other vegetation classes.

Finally, it is apparent that the GEV (and other *extreme* techniques) can be applied Australia wide; and could be used for other fire danger rating systems, not only GFDI in Australia, but also for USA and Canadian fire danger rating systems, commonly used internationally.

Such an approach can an effective tool in developing individual performance solutions or be incorporated into future Bushfire Protection Guidelines, similar to the International Fire Engineering Guidelines currently adopted for fire engineering purposes.

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APPENDICES

APPENDIX 1 - Weather Stations and Site Characteristics

(a) Notes to National Historical Fire Weather Dataset (1972-2015)

National Historical Fire Weather Dataset (see Lucas, 2010)				
Station name NSW RFS Fire Weather Area	Station No(s).	Lat.	Long.	Notes and comments
Bourke Far Western	48013 48239 48245	-30.04	145.95	Site joins in Nov 1994 and Dec 1998. Data begin Mar 1974. Site not used. Elevation: 107.3m
Broken Hill Far Western	47007	-31.98	141.47	Data begin Aug 1973. No data (at all) 1979 through 1985. Elevation: 315.0m
Canberra (ACT)	70014	-35.30	149.20	FFDI data starts June 1972. Few gaps. Elevation: 577.05m
Casino Far North Coast	58063	-28.88	153.05	FFDI data begin February 1986. 692 gaps. Elevation: 20.9m
Cobar Far Western	48027	-31.49	145.83	Data begins June 1972. Elevation: 260.0m
Coffs Harbour Mid North Coast	59040	-30.31	153.12	Data begins June 1972. Elevation: 3.5m
Dubbo Lower Central West Plains	65012 65070	-32.22	148.58	Sites join in Jan 1996. Elevation: 284.0m
Hay Northern Riverina	75031	-34.52	144.85	FFDI data inconsistent May 1973 through Feb 1975. Elevation: 92.0m
Lismore Far North Coast	58037 58214	-28.81	153.26	Sites join in Jan 2003. No FFDI Aug 1986 through Sep 1987. Site not used. Casino used instead.
Mildura (Vic) South Western	76031	-34.23	142.08	Data begins June 1972. Elevation 50.0m
Moree North Western	53048 53115	-29.49	149.85	Sites join in May 1995. Elevation 213.0m
Nowra Illawrra/Sth Coast	68076 68072	-34.95	150.54	Sites join in Dec 2000. Elevation 109.0m
Richmond Greater Sydney	67033 67105	-33.60	150.78	Sites join in Nov 1994. FFDI data begin Feb 1980. Elevation: 19.0m
Sydney AP Greater Sydney	66037	-33.94	151.17	FFDI data begins in June 1972 Elevation 6.0m
Wagga Wagga Eastern Riverina	72150	-35.16	147.46	Data begins June 1972. Elevation: 212.0m
Williamtown Greater Hunter	61078	-32.79	151.84	Data begins June 1972. Elevation 9.0m

(b) Notes to Bureau of Meteorology 3:00pm daily weather dataset (1994-2015)

NSW Combined Bureau of Meteorology Fire Weather Dataset				
Station name NSW RFS Fire Weather Area	Station No(s).	Lat.	Long.	Notes and comments
Grafton Far North Coast	58077 58130	-29.62	152.96	Data combined from two stations from 1-1-1994-31-12-2015.GM dataset from 1917. Elevation: 25.5 m.
Armidale New England	56037 56238 56002	-30.52 -30.52	151.67 151.62	Data available from 1-1-1994 to 31-12-2015. Data combined over three stations to get consolidated GM dataset. Elevation: 1079.7m
Batemans Bay Far South Coast	69134	-35.72	150.19	Data available from 1-1-1994 to 31-12-2015. Elevation: 11.0m
Bathurst Central Ranges	63291	-33.41	149.65	Data available from 1-1-1994 to 31-12-2015 Elevation: 744.5m
Cooma AP Monaro Alpine	70217	-36.29	148.97	Data available from 1-1-1994 to 31-12-2015 Elevation: 930.0m
Coonamble AP Upper Central West Plains	51010 51161	-30.98	148.38	Data available from 1-1-1994 to 31-12-2015. Data combined over two stations to get consolidated GM dataset. Elevation: 181.3m
Deniliquin Southern Riverina	74258 74128	-35.56	144.95	Data available from 1-1-1994 to 31-12-2015. Data combined over two stations to get consolidated GM dataset. Elevation: 94.0m
Goulburn Southern Ranges	70330	-34.81	149.73	Data available from 1-1-1994 to 31-12-2015 Elevation: 640.0m
Tamworth Northern Slopes	55325	-31.07	150.84	Data available from 1-1-1994 to 31-12-2015 Elevation: 394.9m
Young Southern Slopes	73138	-34.25	148.25	Data available from 1-1-1994. to 31-12-2015 Elevation: 379.6m

(c) Additional Notes to Bureau of Meteorology NSW Ground Moisture Data (2009-2015)

BoM Station Number	Rainfall district code	Station Name	Month/Year site opened. (MM/YYYY)	Latitude to 4 decimal places in decimal degrees	Longitude to 4 decimal places in decimal degrees	Method by which latitude/ longitude was derived	State	Height of station above mean sea level in metres	Height of barometer above mean sea level in metres	WMO (World Meteorological Organisation) Index Number
51161	51	COONAMBLE AIRPORT AWS	Sep-97	-30.9776	148.3798	GPS	NSW	181.3	182	95718
55325	55	TAMWORTH AIRPORT AWS	Jan-92	-31.0742	150.8362	GPS	NSW	394.9	395.9	95762
56238	56	ARMIDALE AIRPORT AWS	Jan-93	-30.5273	151.6158	GPS	NSW	1079	1079.6	95773
58077	58	GRAFTON RESEARCH STN	Jan-17	-29.6224	152.9605	GPS	NSW	25	25.6	95571
63291	63	BATHURST AIRPORT AWS	Jan-88	-33.4119	149.654	GPS	NSW	744.5	745	94729
69134	69	BATEMANS BAY (CATALINA COUNTRY CLUB)	Nov-91	-35.7234	150.1872	GPS	NSW	11		94941
70217	70	COOMA AIRPORT AWS	Jan-67	-36.2939	148.9725	GPS	NSW	930	931	94921
70278	70	COOMA VISITORS CENTRE	Jan-73	-36.2318	149.1243	GPS	NSW	778		94923
70330	70	GOULBURN AIRPORT AWS	Nov-88	-34.8085	149.7312	GPS	NSW	640	640.8	95716
73138	73	YOUNG AIRPORT	Dec-88	-34.2493	148.2475	GPS	NSW	379.6	380.6	94712
74258	74	DENILIQUIN AIRPORT AWS	May-97	-35.5575	144.9458	GPS	NSW	94	94.7	95869

APPENDIX 2 - Vegetation Data Resolution and Extent

NSW RFS Fire Area	Spatial Resolution of Vegetation Data	Hectares	Subtable Sum %
Central Ranges	1:25000>scale>=1:50000, patches >=5 ha	368078.5992	11.76%
	1:5000>scale>=1:25000, patches >=1 ha	795975.7918	25.44%
	1:50000>scale>=1:100000, patches >=20 ha	1708852.299	54.61%
	Not specified	104441.7753	3.34%
	scale>=1:100000, patches >=20 ha	20155.5031	0.64%
	scale>=1:5000, patches >=0.5 ha	131495.5254	4.20%
Eastern Riverina	1:25000>scale>=1:50000, patches >=2 ha	369237.6305	20.26%
	1:25000>scale>=1:50000, patches >=5 ha	383955.5957	21.06%
	1:5000>scale>=1:25000, patches >=1 ha	1069083.11	58.65%
	1:50000>scale>=1:100000, patches >=20 ha	6.2417	0.00%
	Not mapped	483.6635	0.03%
	Not specified	30.8526	0.00%
Far North Coast	1:25000>scale>=1:50000, patches >=5 ha	1698642.03	81.68%
	1:5000>scale>=1:25000, patches >=1 ha	344780.3745	16.58%
	Not mapped	16337.8293	0.79%
	Not specified	11159.3593	0.54%
	scale>=1:5000, patches >=0.5 ha	8593.2575	0.41%
Far South Coast	1:25000>scale>=1:50000, patches >=5 ha	2398.4741	0.25%
	1:5000>scale>=1:25000, patches >=1 ha	962491.7287	98.89%
	Not mapped	3873.4584	0.40%
	Not specified	370.1643	0.04%
	scale>=1:5000, patches >=0.5 ha	4157.1365	0.43%
Far Western	1:25000>scale>=1:50000, patches >=5 ha	4133015.912	16.32%
	1:5000>scale>=1:25000, patches >=1 ha	88346.0929	0.35%
	1:50000>scale>=1:100000, patches >=0.5 ha	133624.7857	0.53%
	1:50000>scale>=1:100000, patches >=20 ha	3841693.738	15.17%
	Not mapped	2936.99	0.01%
	Not specified	583862.2888	2.31%
	scale>=1:100000, patches >=20 ha	16540208.76	65.32%
Greater Hunter	1:25000>scale>=1:50000, patches >=5 ha	38984.9367	1.70%

	1:5000>scale>=1:25000, patches >=1 ha	2217243.949	96.78%
	Not mapped	20084.2198	0.88%
	Not specified	6919.3899	0.30%
	scale>=1:5000, patches >=0.5 ha	7833.8156	0.34%
Greater Sydney District	1:25000>scale>=1:50000, patches >=5 ha	53517.6517	5.39%
	1:5000>scale>=1:25000, patches >=1 ha	731163.8477	73.69%
	1:50000>scale>=1:100000, patches >=20 ha	128.6316	0.01%
	Not mapped	27056.9515	2.73%
	Not specified	3082.9818	0.31%
	scale>=1:5000, patches >=0.5 ha	177282.3003	17.87%
Illawarra / Shoalhaven	1:25000>scale>=1:50000, patches >=5 ha	3628.2904	0.33%
	1:5000>scale>=1:25000, patches >=1 ha	1070288.244	96.23%
	1:50000>scale>=1:100000, patches >=20 ha	12.8277	0.00%
	Not mapped	12303.2291	1.11%
	Not specified	703.4912	0.06%
	scale>=1:5000, patches >=0.5 ha	25227.4342	2.27%
Lord Howe Island	1:5000>scale>=1:25000, patches >=1 ha	1388.8855	83.99%
	Not mapped	55.6705	3.37%
	Not specified	209.0878	12.64%
Lower Central West Plains	1:25000>scale>=1:50000, patches >=5 ha	411259.8865	7.74%
	1:5000>scale>=1:25000, patches >=1 ha	332298.5703	6.26%
	1:50000>scale>=1:100000, patches >=20 ha	4261593.388	80.24%
	Not specified	175123.9487	3.30%
	scale>=1:100000, patches >=20 ha	35351.8682	0.67%
	scale>=1:5000, patches >=0.5 ha	95290.8873	1.79%
Monaro Alpine	1:25000>scale>=1:50000, patches >=5 ha	1191303.278	78.46%
	1:5000>scale>=1:25000, patches >=1 ha	308691.8042	20.33%
	Not mapped	329.4004	0.02%
	Not specified	7301.7386	0.48%
	scale>=1:100000, patches >=20 ha	10755.8722	0.71%
New England	1:25000>scale>=1:50000, patches >=5 ha	2245003.304	72.53%

	1:5000>scale>=1:25000, patches >=1 ha	560601.4058	18.11%
	Not mapped	1140.6894	0.04%
	Not specified	227003.0864	7.33%
	scale>=1:100000, patches >=20 ha	19150.8133	0.62%
	scale>=1:5000, patches >=0.5 ha	42502.3275	1.37%
North Coast	1:25000>scale>=1:50000, patches >=5 ha	629633.3391	29.46%
	1:5000>scale>=1:25000, patches >=1 ha	1420599.9	66.47%
	1:50000>scale>=1:100000, patches >=20 ha	3.0038	0.00%
	Not mapped	20908.7822	0.98%
	Not specified	12138.541	0.57%
	scale>=1:5000, patches >=0.5 ha	53901.9431	2.52%
North Western	1:25000>scale>=1:50000, patches >=5 ha	1624218.012	24.72%
	1:5000>scale>=1:25000, patches >=1 ha	453242.9324	6.90%
	1:50000>scale>=1:100000, patches >=20 ha	4132257.073	62.90%
	Not mapped	910.2046	0.01%
	Not specified	358608.0888	5.46%
Northern Riverina	1:25000>scale>=1:50000, patches >=2 ha	10843.0965	0.27%
	1:25000>scale>=1:50000, patches >=5 ha	1333809.899	32.83%
	1:5000>scale>=1:25000, patches >=1 ha	594926.4527	14.64%
	1:50000>scale>=1:100000, patches >=20 ha	740728.6876	18.23%
	Not specified	343133.0929	8.45%
	scale>=1:100000, patches >=20 ha	1039041.944	25.58%
Northern Slopes	1:25000>scale>=1:50000, patches >=5 ha	2296167.78	60.68%
	1:5000>scale>=1:25000, patches >=1 ha	1280635.182	33.84%
	1:50000>scale>=1:100000, patches >=20 ha	182778.9008	4.83%
	Not mapped	657.0041	0.02%
	Not specified	23951.2713	0.63%
	scale>=1:100000, patches >=20 ha	148.2508	0.00%
South Western	1:25000>scale>=1:50000, patches >=2 ha	23399.9354	0.49%
	1:25000>scale>=1:50000, patches >=5 ha	134629.3691	2.81%
	1:5000>scale>=1:25000, patches >=1 ha	207200.1884	4.33%
	1:50000>scale>=1:100000, patches >=0.5 ha	123516.3675	2.58%

	1:50000>scale>=1:100000, patches >=20 ha	43156.9087	0.90%
	Not mapped	857.452	0.02%
	Not specified	1.0402	0.00%
	scale>=1:100000, patches >=20 ha	4250653.174	88.86%
Southern Ranges	1:25000>scale>=1:50000, patches >=5 ha	991953.692	50.50%
	1:5000>scale>=1:25000, patches >=1 ha	970184.5187	49.39%
	1:50000>scale>=1:100000, patches >=20 ha	1251.2634	0.06%
	Not specified	168.5187	0.01%
	scale>=1:100000, patches >=20 ha	691.2308	0.04%
Southern Riverina	1:25000>scale>=1:50000, patches >=2 ha	2332221.953	73.23%
	1:25000>scale>=1:50000, patches >=5 ha	459871.4773	14.44%
	1:5000>scale>=1:25000, patches >=1 ha	76356.0452	2.40%
	Not mapped	8.1011	0.00%
	Not specified	2.1763	0.00%
	scale>=1:100000, patches >=20 ha	316496.2255	9.94%
Southern Slopes	1:25000>scale>=1:50000, patches >=5 ha	1476563.318	73.51%
	1:5000>scale>=1:25000, patches >=1 ha	529855.5732	26.38%
	1:50000>scale>=1:100000, patches >=20 ha	32.5388	0.00%
	Not mapped	1931.9188	0.10%
	Not specified	353.4982	0.02%
	scale>=1:100000, patches >=20 ha	38.0584	0.00%
Upper Central West Plains	1:25000>scale>=1:50000, patches >=5 ha	47697.7126	1.19%
	1:5000>scale>=1:25000, patches >=1 ha	23344.2658	0.58%
	1:50000>scale>=1:100000, patches >=20 ha	3731236.78	93.11%
	Not specified	205245.7703	5.12%
	scale>=1:100000, patches >=20 ha	8.1854	0.00%

APPENDIX 3 -NSW Forest and Woodland Vegetation Classes by NSW Fire Weather District

1. Far North Coast	**Formation**	**Class**	**Hectares**
	Dry sclerophyll forests (Shrub/grass sub-formation)	Clarence Dry Sclerophyll Forests New England Dry Sclerophyll Forests Northern Gorge Dry Sclerophyll Forests	274973.584 6045.3151 77839.5591
	Dry sclerophyll forests (Shrubby sub-formation)	Coastal Dune Dry Sclerophyll Forests North Coast Dry Sclerophyll Forests Northern Escarpment Dry Sclerophyll Forests Northern Tableland Dry Sclerophyll Forests	8347.3064 124323.7827 2074.4039 14246.5346
	Grassy woodlands	Coastal Valley Grassy Woodlands New England Grassy Woodlands Subalpine Woodlands Tableland Clay Grassy Woodlands	44146.4586 4.3919 395.9649 42.3286
	Wet sclerophyll forests (Grassy sub-formation)	Northern Hinterland Wet Sclerophyll Forests Northern Tableland Wet Sclerophyll Forests	168289.9192 40551.2123
	Wet sclerophyll forests (Shrubby sub-formation)	North Coast Wet Sclerophyll Forests Northern Escarpment Wet Sclerophyll Forests	174766.1028 12584.0217

2. North Coast	**Formation**	**Class**	**Hectares**
	Dry sclerophyll forests (Shrub/grass sub-formation)	Clarence Dry Sclerophyll Forests Hunter-Macleay Dry Sclerophyll Forests New England Dry Sclerophyll Forests Northern Gorge Dry Sclerophyll Forests	3283.291 26653.1706 42.6126 46453.2933
	Dry sclerophyll forests (Shrubby sub-formation)	Coastal Dune Dry Sclerophyll Forests North Coast Dry Sclerophyll Forests Northern Escarpment Dry Sclerophyll Forests Northern Tableland Dry Sclerophyll Forests Sydney Coastal Dry Sclerophyll Forests Sydney Hinterland Dry Sclerophyll Forests	18706.5079 8877.7435 1277.9185 1508.963 15300.1477 4.6295
	Grassy woodlands	Coastal Valley Grassy Woodlands New England Grassy Woodlands Subalpine Woodlands Tableland Clay Grassy Woodlands Western Slopes Grassy Woodlands	12681.2729 369.0591 2175.3648 103.0679 150.3555
	Wet sclerophyll forests (Grassy sub-formation)	Northern Hinterland Wet Sclerophyll Forests Northern Tableland Wet Sclerophyll Forests	510837.0918 42867.8452
	Wet sclerophyll forests (Shrubby sub-formation)	North Coast Wet Sclerophyll Forests Northern Escarpment Wet Sclerophyll Forests	383540.0033 45209.0297

3. Greater Hunter	Formation	Class	Hectares
	Dry sclerophyll forests (Shrub/grass sub-formation)	Central Gorge Dry Sclerophyll Forests	32717.4287
		Cumberland Dry Sclerophyll Forests	30.0012
		Hunter-Macleay Dry Sclerophyll Forests	117903.4126
		North-west Slopes Dry Sclerophyll Woodlands	138551.6965
		Northern Gorge Dry Sclerophyll Forests	2057.5951
	Dry sclerophyll forests (Shrubby sub-formation)	Coastal Dune Dry Sclerophyll Forests	9712.5216
		Northern Escarpment Dry Sclerophyll Forests	264.4779
		Northern Tableland Dry Sclerophyll Forests	1353.8846
		Southern Tableland Dry Sclerophyll Forests	48.2312
		Sydney Coastal Dry Sclerophyll Forests	39019.5667
		Sydney Hinterland Dry Sclerophyll Forests	304822.4862
		Sydney Montane Dry Sclerophyll Forests	3886.9874
		Sydney Sand Flats Dry Sclerophyll Forests	7073.9665
		Western Slopes Dry Sclerophyll Forests	126793.3503
	Grassy woodlands	Coastal Valley Grassy Woodlands	17044.1437
		New England Grassy Woodlands	83190.2444
		Subalpine Woodlands	247.2182
		Tableland Clay Grassy Woodlands	772.2667
		Western Slopes Grassy Woodlands	66619.4702
	Wet sclerophyll forests (Grassy sub-formation)	Northern Hinterland Wet Sclerophyll Forests	61172.0263
		Northern Tableland Wet Sclerophyll Forests	49983.4439
		Southern Tableland Wet Sclerophyll Forests	2361.1766
	Wet sclerophyll forests (Shrubby sub-formation)	North Coast Wet Sclerophyll Forests	100540.8542
		Northern Escarpment Wet Sclerophyll Forests	23475.3267
		Southern Escarpment Wet Sclerophyll Forests	915.1989

4. Greater Sydney District	**Formation**	**Class**	**Hectares**
	Dry sclerophyll forests (Shrub/grass sub-formation)	Central Gorge Dry Sclerophyll Forests Cumberland Dry Sclerophyll Forests Hunter-Macleay Dry Sclerophyll Forests	12350.9496 3097.5662 4189.665
	Dry sclerophyll forests (Shrubby sub-formation)	Coastal Dune Dry Sclerophyll Forests South Coast Sands Dry Sclerophyll Forests Sydney Coastal Dry Sclerophyll Forests Sydney Hinterland Dry Sclerophyll Forests Sydney Montane Dry Sclerophyll Forests Sydney Sand Flats Dry Sclerophyll Forests Western Slopes Dry Sclerophyll Forests	940.1112 49.6309 127998.2376 275941.1666 28956.7531 12739.9784 33.236
	Grassy woodlands	Coastal Valley Grassy Woodlands Southern Tableland Grassy Woodlands Western Slopes Grassy Woodlands	12383.1244 449.9599 55.7
	Wet sclerophyll forests (Grassy sub-formation)	Northern Hinterland Wet Sclerophyll Forests Southern Tableland Wet Sclerophyll Forests	44717.6182 1122.9872
	Wet sclerophyll forests (Shrubby sub-formation)	North Coast Wet Sclerophyll Forests Southern Escarpment Wet Sclerophyll Forests	49781.6677 1006.4512

5. Illawarra / Shoalhaven	Formation	Class	Hectares
	Dry sclerophyll forests (Shrub/grass sub-formation)	Central Gorge Dry Sclerophyll Forests	124636.7537
		Cumberland Dry Sclerophyll Forests	2192.4962
	Dry sclerophyll forests (Shrubby sub-formation)	Coastal Dune Dry Sclerophyll Forests	9.9003
		South Coast Sands Dry Sclerophyll Forests	7387.7537
		South East Dry Sclerophyll Forests	65041.2206
		Southern Tableland Dry Sclerophyll Forests	1502.2813
		Sydney Coastal Dry Sclerophyll Forests	116085.3814
		Sydney Hinterland Dry Sclerophyll Forests	142462.1735
		Sydney Montane Dry Sclerophyll Forests	31457.0339
		Sydney Sand Flats Dry Sclerophyll Forests	281.4708
	Grassy woodlands	Coastal Valley Grassy Woodlands	9993.2115
		Southern Tableland Grassy Woodlands	3587.1059
		Tableland Clay Grassy Woodlands	671.1298
	Wet sclerophyll forests (Grassy sub-formation)	Montane Wet Sclerophyll Forests	227.3333
		Northern Hinterland Wet Sclerophyll Forests	1423.2876
		Southern Lowland Wet Sclerophyll Forests	100740.3188
		Southern Tableland Wet Sclerophyll Forests	14808.9966
	Wet sclerophyll forests (Shrubby sub-formation)	North Coast Wet Sclerophyll Forests	39759.1935
		South Coast Wet Sclerophyll Forests	38489.5892
		Southern Escarpment Wet Sclerophyll Forests	2923.9852
5. Jervis Bay Territory within Illawarra/ South Coast	Dry sclerophyll forests (Shrubby sub-formation)	Coastal Dune Dry Sclerophyll Forests	0.1057
		South Coast Sands Dry Sclerophyll Forests	3055.3521
		South East Dry Sclerophyll Forests	892.9306
		Sydney Coastal Dry Sclerophyll Forests	2.4168
	Wet sclerophyll forests (Shrubby sub-formation)	North Coast Wet Sclerophyll Forests	77.1359

6. Far South Coast	Formation	Class	Hectares
	Dry sclerophyll forests (Shrub/grass sub-formation)	Southern Hinterland Dry Sclerophyll Forests	72263.0198
	Dry sclerophyll forests (Shrubby sub-formation)	South Coast Sands Dry Sclerophyll Forests	2556.7859
		South East Dry Sclerophyll Forests	292350.3428
		Southern Wattle Dry Sclerophyll Forests	5159.0396
		Sydney Coastal Dry Sclerophyll Forests	6.4524
		Sydney Montane Dry Sclerophyll Forests	190.2849
	Grassy woodlands	Coastal Valley Grassy Woodlands	13904.26
		Subalpine Woodlands	1015.1386
		Tableland Clay Grassy Woodlands	17420.8223
	Wet sclerophyll forests (Grassy sub-formation)	Montane Wet Sclerophyll Forests	2607.6503
		Southern Lowland Wet Sclerophyll Forests	79037.2039
		Southern Tableland Wet Sclerophyll Forests	2766.0168
	Wet sclerophyll forests (Shrubby sub-formation)	South Coast Wet Sclerophyll Forests	170833.3908
		Southern Escarpment Wet Sclerophyll Forests	80946.2724

7. Monaro Alpine	**Formation**	**Class**	**Hectares**
	Dry sclerophyll forests (Shrub/grass sub-formation)	Southern Hinterland Dry Sclerophyll Forests	2948.9605
		Upper Riverina Dry Sclerophyll Forests	37683.2117
	Dry sclerophyll forests (Shrubby sub-formation)	South Coast Sands Dry Sclerophyll Forests	2.0716
		South East Dry Sclerophyll Forests	12892.8545
		Southern Tableland Dry Sclerophyll Forests	207759.118
		Southern Wattle Dry Sclerophyll Forests	1274.7594
	Grassy woodlands	Southern Tableland Grassy Woodlands	200.0647
		Subalpine Woodlands	202027.6313
		Tableland Clay Grassy Woodlands	78163.5501
	Wet sclerophyll forests (Grassy sub-formation)	Montane Wet Sclerophyll Forests	14817.7439
		Southern Tableland Wet Sclerophyll Forests	40707.0449
	Wet sclerophyll forests (Shrubby sub-formation)	South Coast Wet Sclerophyll Forests	491.1407
		Southern Escarpment Wet Sclerophyll Forests	51554.9391

8. Australian Capital Territory	**Formation**	**Class**	**Hectares**
	Dry sclerophyll forests (Shrubby sub-formation)	Southern Tableland Dry Sclerophyll Forests	31708.5228
	Grassy woodlands	Southern Tableland Grassy Woodlands Subalpine Woodlands Tableland Clay Grassy Woodlands	2499.4978 52920.001 5.7796
	Wet sclerophyll forests (Grassy sub-formation)	Southern Tableland Wet Sclerophyll Forests	30902.7414
	Wet sclerophyll forests (Shrubby sub-formation)	Southern Escarpment Wet Sclerophyll Forests	2689.9397

9. Southern Ranges	**Formation**	**Class**	**Hectares**
	Dry sclerophyll forests (Shrub/grass sub-formation)	Central Gorge Dry Sclerophyll Forests	42765.2033
		Southern Hinterland Dry Sclerophyll Forests	8572.4695
		Upper Riverina Dry Sclerophyll Forests	5920.9116
	Dry sclerophyll forests (Shrubby sub-formation)	South East Dry Sclerophyll Forests	75350.6241
		Southern Tableland Dry Sclerophyll Forests	277803.5219
		Sydney Coastal Dry Sclerophyll Forests	1004.7678
		Sydney Hinterland Dry Sclerophyll Forests	633.6943
		Sydney Montane Dry Sclerophyll Forests	6171.6798
	Grassy woodlands	Coastal Valley Grassy Woodlands	852.3128
		Southern Tableland Grassy Woodlands	43918.1084
		Subalpine Woodlands	6580.5535
		Tableland Clay Grassy Woodlands	30785.8945
		Western Slopes Grassy Woodlands	5094.5903
	Wet sclerophyll forests (Grassy sub-formation)	Montane Wet Sclerophyll Forests	758.2097
		Southern Lowland Wet Sclerophyll Forests	2084.1853
		Southern Tableland Wet Sclerophyll Forests	25337.1731
	Wet sclerophyll forests (Shrubby sub-formation)	South Coast Wet Sclerophyll Forests	1941.6351
		Southern Escarpment Wet Sclerophyll Forests	55977.8135

10. Central Ranges	**Formation**	**Class**	**Hectares**
	Dry sclerophyll forests (Shrub/grass sub-formation)	Central Gorge Dry Sclerophyll Forests Hunter-Macleay Dry Sclerophyll Forests North-west Slopes Dry Sclerophyll Woodlands Upper Riverina Dry Sclerophyll Forests	58446.1056 16.9036 50183.3532 30692.2821
	Dry sclerophyll forests (Shrubby sub-formation)	South East Dry Sclerophyll Forests Southern Tableland Dry Sclerophyll Forests Sydney Coastal Dry Sclerophyll Forests Sydney Hinterland Dry Sclerophyll Forests Sydney Montane Dry Sclerophyll Forests Sydney Sand Flats Dry Sclerophyll Forests Western Slopes Dry Sclerophyll Forests	14017.6821 216042.6756 47836.9858 67283.1142 58340.735 47.4774 231146.8104
	Grassy woodlands	Coastal Valley Grassy Woodlands Floodplain Transition Woodlands Southern Tableland Grassy Woodlands Subalpine Woodlands Tableland Clay Grassy Woodlands Western Slopes Grassy Woodlands	659.7683 1941.5434 53473.0954 7095.8159 5155.4814 23540.4977
	Wet sclerophyll forests (Grassy sub-formation)	Northern Hinterland Wet Sclerophyll Forests Southern Tableland Wet Sclerophyll Forests	184.3326 80335.7162
	Wet sclerophyll forests (Shrubby sub-formation)	North Coast Wet Sclerophyll Forests Southern Escarpment Wet Sclerophyll Forests	10123.6638 8423.8298

11. New England	Formation	Class	Hectares
	Dry sclerophyll forests (Shrub/grass sub-formation)	Clarence Dry Sclerophyll Forests	22334.899
		Hunter-Macleay Dry Sclerophyll Forests	149.6715
		New England Dry Sclerophyll Forests	154370.0063
		North-west Slopes Dry Sclerophyll Woodlands	34285.0003
		Northern Gorge Dry Sclerophyll Forests	285263.6697
	Dry sclerophyll forests (Shrubby sub-formation)	North Coast Dry Sclerophyll Forests	2610.5565
		Northern Escarpment Dry Sclerophyll Forests	38593.6678
		Northern Tableland Dry Sclerophyll Forests	314829.9076
	Grassy woodlands	Coastal Valley Grassy Woodlands	6408.0893
		New England Grassy Woodlands	92166.6385
		Subalpine Woodlands	14211.9668
		Tableland Clay Grassy Woodlands	11739.2657
		Western Slopes Grassy Woodlands	14056.7932
	Wet sclerophyll forests (Grassy sub-formation)	Northern Hinterland Wet Sclerophyll Forests	40596.3869
		Northern Tableland Wet Sclerophyll Forests	218549.3043
	Wet sclerophyll forests (Shrubby sub-formation)	North Coast Wet Sclerophyll Forests	48307.5248
		Northern Escarpment Wet Sclerophyll Forests	49279.0370

12. Northern Slopes	Formation	Class	Hectares
	Dry sclerophyll forests (Shrub/grass sub-formation)	New England Dry Sclerophyll Forests	436.2966
		North-west Slopes Dry Sclerophyll Woodlands	426863.9392
		Northern Gorge Dry Sclerophyll Forests	152.8817
	Dry sclerophyll forests (Shrubby sub-formation)	Northern Escarpment Dry Sclerophyll Forests	45.2513
		Northern Tableland Dry Sclerophyll Forests	219701.0927
		Western Slopes Dry Sclerophyll Forests	63514.1273
		Yetman Dry Sclerophyll Forests	77796.2011
	Grassy woodlands	Floodplain Transition Woodlands	19435.8193
		New England Grassy Woodlands	112697.7539
		Subalpine Woodlands	46.2887
		Tableland Clay Grassy Woodlands	2873.8848
		Western Slopes Grassy Woodlands	242071.3217
	Wet sclerophyll forests (Grassy sub-formation)	Northern Hinterland Wet Sclerophyll Forests	0.1202
		Northern Tableland Wet Sclerophyll Forests	30350.0191
	Wet sclerophyll forests (Shrubby sub-formation)	North Coast Wet Sclerophyll Forests	27.0292
		Northern Escarpment Wet Sclerophyll Forests	1088.3594

13. North Western	Formation	Class	Hectares
	Dry sclerophyll forests (Shrub/grass sub-formation)	North-west Slopes Dry Sclerophyll Woodlands	139420.7606
		Pilliga Outwash Dry Sclerophyll Forests	194228.5247
		Upper Riverina Dry Sclerophyll Forests	709.0201
	Dry sclerophyll forests (Shrubby sub-formation)	Northern Tableland Dry Sclerophyll Forests	8414.7948
		Western Slopes Dry Sclerophyll Forests	679461.3498
		Yetman Dry Sclerophyll Forests	4792.0647
	Grassy woodlands	Floodplain Transition Woodlands	11686.6256
		New England Grassy Woodlands	359.6161
		Southern Tableland Grassy Woodlands	2.6968
		Tableland Clay Grassy Woodlands	695.4755
		Western Slopes Grassy Woodlands	81225.7572
	Wet sclerophyll forests (Grassy sub-formation)	Northern Tableland Wet Sclerophyll Forests	11841.7702

14. Upper Central West Plains	**Formation**	**Class**	**Hectares**
	Dry sclerophyll forests (Shrub/grass sub-formation)	North-west Slopes Dry Sclerophyll Woodlands Pilliga Outwash Dry Sclerophyll Forests	19518.4292 83699.7896
	Dry sclerophyll forests (Shrubby sub-formation)	Western Slopes Dry Sclerophyll Forests	37840.5455
	Grassy woodlands	Floodplain Transition Woodlands Southern Tableland Grassy Woodlands Western Slopes Grassy Woodlands	19407.7932 606.2031 6052.3377
	Wet sclerophyll forests (Grassy sub-formation)	Northern Tableland Wet Sclerophyll Forests	217.9253

15. Lower Central West Plains	**Formation**	**Class**	**Hectares**
	Dry sclerophyll forests (Shrub/grass sub-formation)	North-west Slopes Dry Sclerophyll Woodlands Pilliga Outwash Dry Sclerophyll Forests Upper Riverina Dry Sclerophyll Forests	7746.8279 37003.8188 21249.6796
	Dry sclerophyll forests (Shrubby sub-formation)	Southern Tableland Dry Sclerophyll Forests Western Slopes Dry Sclerophyll Forests	7885.9801 153929.9761
	Grassy woodlands	Floodplain Transition Woodlands Southern Tableland Grassy Woodlands Western Slopes Grassy Woodlands	85508.4083 10733.1083 7155.1875
	Wet sclerophyll forests (Grassy sub-formation)	Northern Tableland Wet Sclerophyll Forests	58.048

16. Southern Slopes	**Formation**	**Class**	**Hectares**
	Dry sclerophyll forests (Shrub/grass sub-formation)	Upper Riverina Dry Sclerophyll Forests	79031.9139
	Dry sclerophyll forests (Shrubby sub-formation)	Southern Tableland Dry Sclerophyll Forest Western Slopes Dry Sclerophyll Forests	145812.5635 10736.6721
	Grassy woodlands	Floodplain Transition Woodlands Southern Tableland Grassy Woodlands Subalpine Woodlands Western Slopes Grassy Woodlands	2502.1111 41691.2541 104818.5585 41539.8396
	Wet sclerophyll forests (Grassy sub-formation)	Montane Wet Sclerophyll Forests Southern Tableland Wet Sclerophyll Forests	60565.645 89642.071
	Wet sclerophyll forests (Shrubby sub-formation)	Southern Escarpment Wet Sclerophyll Forests	2325.2618

17. Eastern Riverina	**Formation**	**Class**	**Hectares**
	Dry sclerophyll forests (Shrub/grass sub-formation)	Upper Riverina Dry Sclerophyll Forests	74827.5926
	Dry sclerophyll forests (Shrubby sub-formation)	Southern Tableland Dry Sclerophyll Forests Western Slopes Dry Sclerophyll Forests	28135.2777 6476.6884
	Grassy woodlands	Floodplain Transition Woodlands Southern Tableland Grassy Woodlands Western Slopes Grassy Woodlands	35494.6253 15624.2724 24026.6089
	Wet sclerophyll forests (Grassy sub-formation)	Southern Tableland Wet Sclerophyll Forests	14.5896

18. Southern Riverina	**Formation**	**Class**	**Hectares**
	Grassy woodlands	Floodplain Transition Woodlands Western Slopes Grassy Woodlands	53679.531 131.2095

19. Northern Riverina	Formation	Class	Hectares
	Dry sclerophyll forests (Shrub/grass sub-formation)	Upper Riverina Dry Sclerophyll Forests	147.4309
	Dry sclerophyll forests (Shrubby sub-formation)	Western Slopes Dry Sclerophyll Forests	18169.5689
	Grassy woodlands	Floodplain Transition Woodlands	28303.3959

20. South Western	Formation	Class	Hectares

21. Far Western	Formation	Class	Hectares
	Dry sclerophyll forests (Shrub/grass sub-formation)	North-west Slopes Dry Sclerophyll Woodlands	90.8487
	Dry sclerophyll forests (Shrubby sub-formation)	Western Slopes Dry Sclerophyll Forests	296.9041
	Grassy woodlands	Floodplain Transition Woodlands	7276.4214

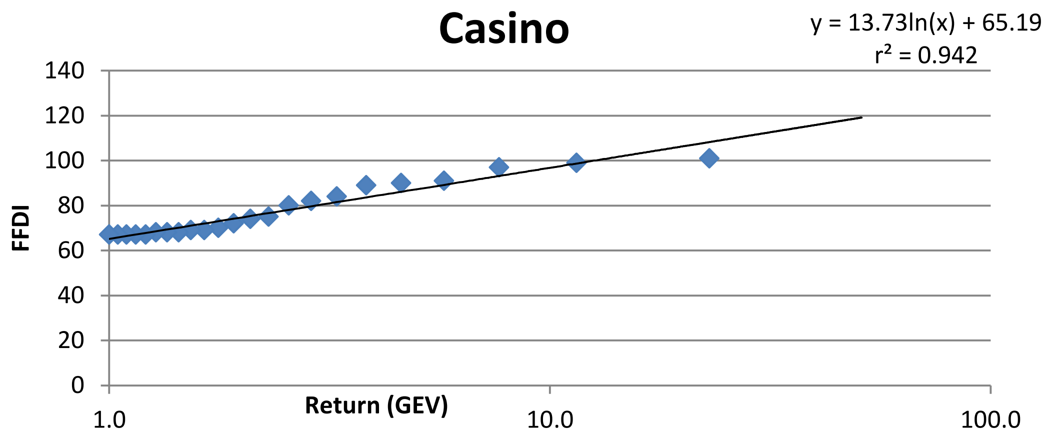
APPENDIX 4 - Shape Curve Parametersand Intercept for Amax, GEV and GPDfor FFDI

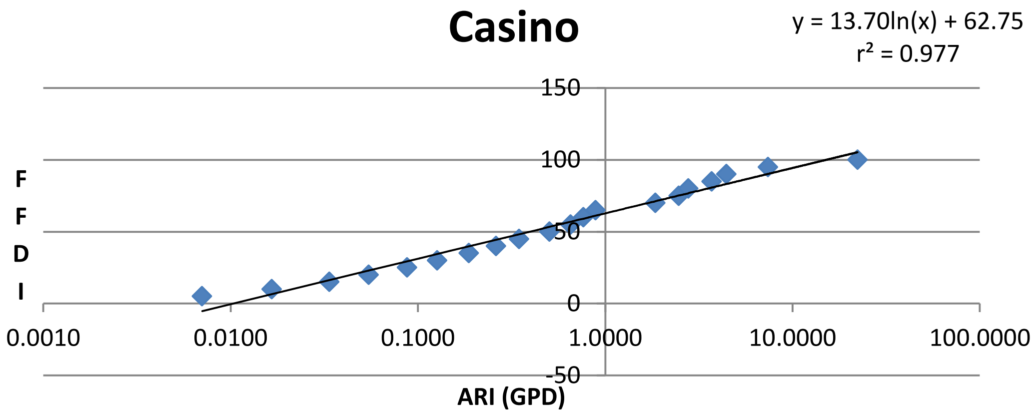
Fire Weather District Data: 1972-2009	Station	Annual Max (Recurrence)				GEV (Return Period)				Pareto (Annual Return Interval)			
		α	β	r^2	1:50	α	β	r^2	1:50	α	β	r^2	1:50
1. Far North Coast	Grafton	24.61	24.06	0.9598	120	13.99	46.63	0.971	101	11.26	50.779	0.9523	94
2. North Coast	Coffs Harbour	21.02	11.58	0.9573	94	18.23	24.30	0.9722	96	11.75	36.21	0.9205	82
3. Greater Hunter	Williamtown	21.76	36.27	0.8761	121	12.68	55.54	0.9769	106	11.99	54.11	0.9892	101
4. Greater Sydney	Sydney Airport	18.22	38.78	0.8512	110	10.63	54.88	0.9846	98	11.31	52.00	0.9812	96
5. Illawarra/South Coast	Nowra	22.50	33.70	0.9520	122	16.30	49.31	0.9460	112	12.96	53.47	0.9734	104
6. Far South Coast	Batemans Bay	22.83	22.78	0.9042	112	14.70	38.72	0.9617	97	11.58	45.04	0.9581	90
7. Monaro-Alpine	Cooma	18.76	28.76	0.8117	96	7.09	51.22	0.9157	83	8.643	49.90	0.9966	84
8. ACT	Canberra Airport	20.97	32.71	0.9341	115	13.57	49.64	0.9676	100	10.61	53.74	0.9906	96
9. Southern Ranges	Goulburn	20.48	41.07	0.8499	121	10.97	61.93	0.9565	105	10.92	61.70	0.9946	104
10. Central Ranges	Bathurst	17.60	31.61	0.8973	100	8.694	48.39	0.9696	83	8.571	48.28	0.9972	82
11. New England	Armidale	9.97	13.42	0.9296	52	7.72	21.75	0.9566	46	5.146	25.78	0.9473	46
12. Northern Ranges	Tamworth	21.19	37.65	0.9494	101	14.57	53.84	0.9221	100	10.3	59.45	0.9801	100
13. North Western	Moree	23.70	32.58	0.9602	104	16.93	48.98	0.9134	115	11.71	58.13	0.9442	103
14. Upper Central West Plains	Coonamble	31.11	40.91	0.9554	163	22.22	59.51	0.9679	123	12.83	70.94	0.97	121
15. Lower Central West Plains	Dubbo	22.52	32.57	0.9618	121	13.22	55.62	0.9863	107	10.90	58.54	0.9925	101
16. Southern Slopes	Young	14.04	41.71	0.712	97	5.67	56.85	0.9545	79	8.85	54.7	0.9952	89
17. Eastern Riverina	Wagga Wagga	25.39	45.07	0.9505	144	15.98	65.88	0.9396	122	13.22	69.4	0.9815	121
18. Southern Riverina	Deniliquin	22.29	58.67	0.9471	146	13.64	76.88	0.9398	131	12.61	75.7	0.9956	125
19. Northern Riverina	Hay	23.7	32.58	0.9602	125	16.93	48.98	0.9159	108	12.13	58.96	0.9375	106
20. South Western	Mildura	23.73	57.66	0.8658	150	14.78	76.92	0.917	136	13.54	77.86	0.9861	130
21. Far Western	Cobar	20.29	48.86	0.9529	128	13.07	60.73	0.9382	116	11.41	68.14	0.9862	113

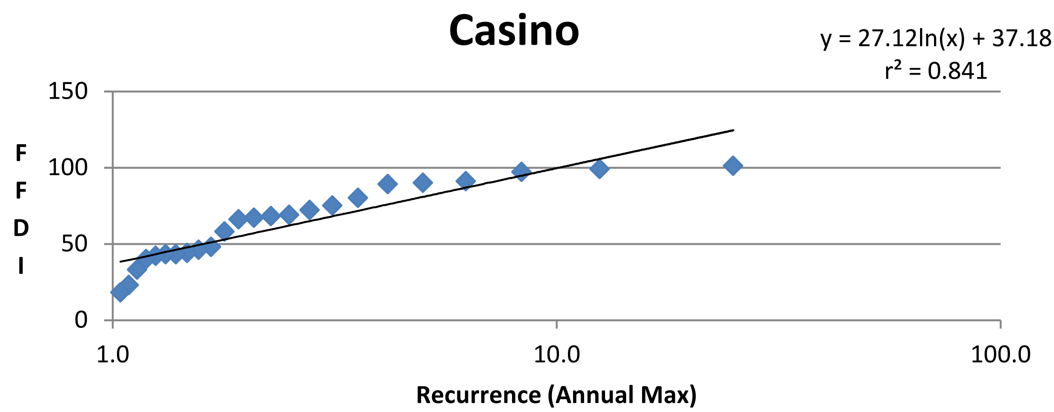
APPENDIX 5 - *Extreme* Value Assessment Curves (FFDIs)

Fire Weather District 1: Far North Coast

Weather Station: Casino. (Lucas, 2010), Years of data: 24, Highest FFDI Value: 101

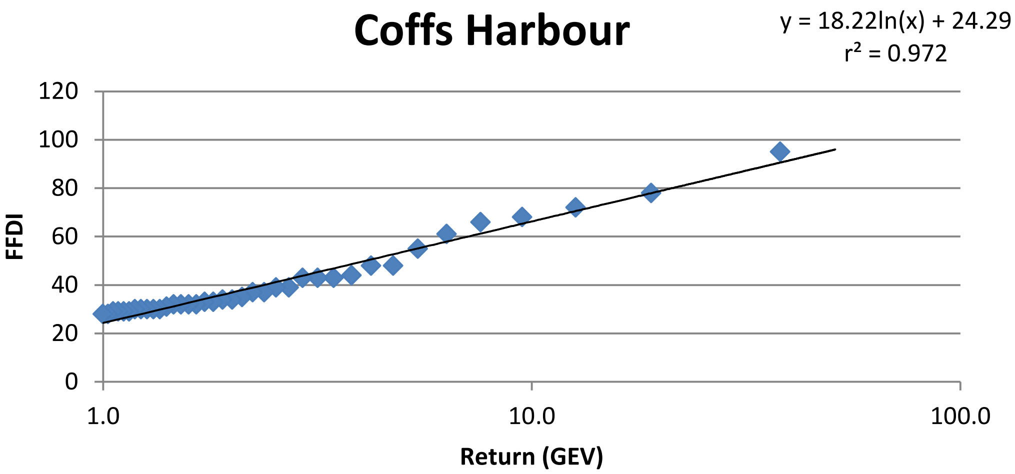


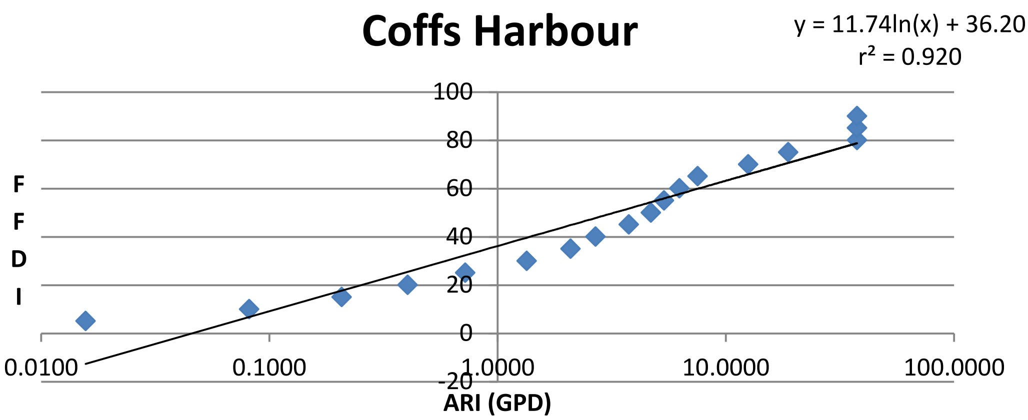


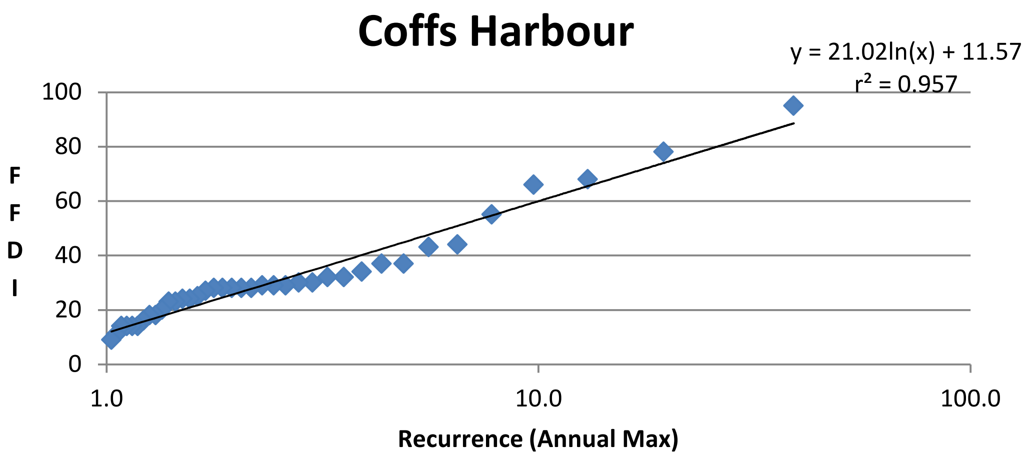


Fire Weather District 2: North Coast.

Weather Station: Coffs Harbour (Lucas, 2010), Years of data: 37.5, Highest FFDI Value: 95.

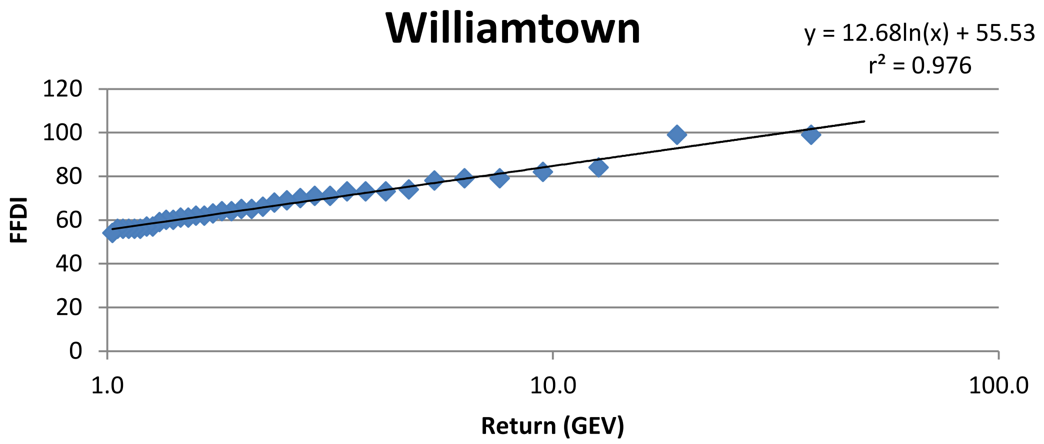


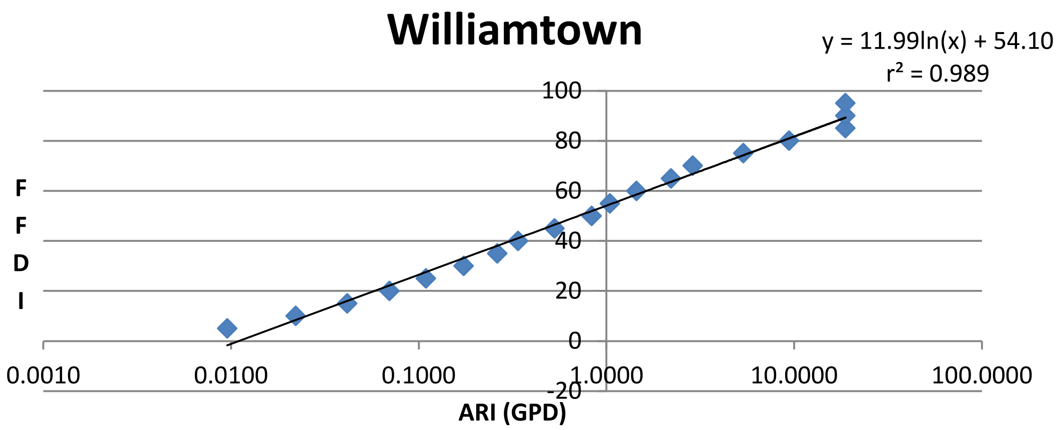


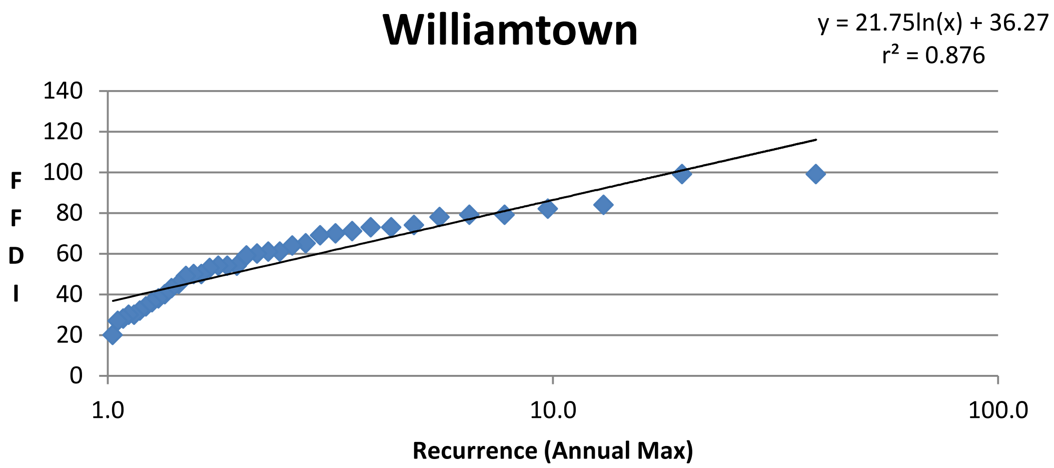


Fire Weather District 3: Greater Hunter.

Weather Station: Williamtown (Lucas, 2010), Years of data: 37, Highest FFDI Value: 99

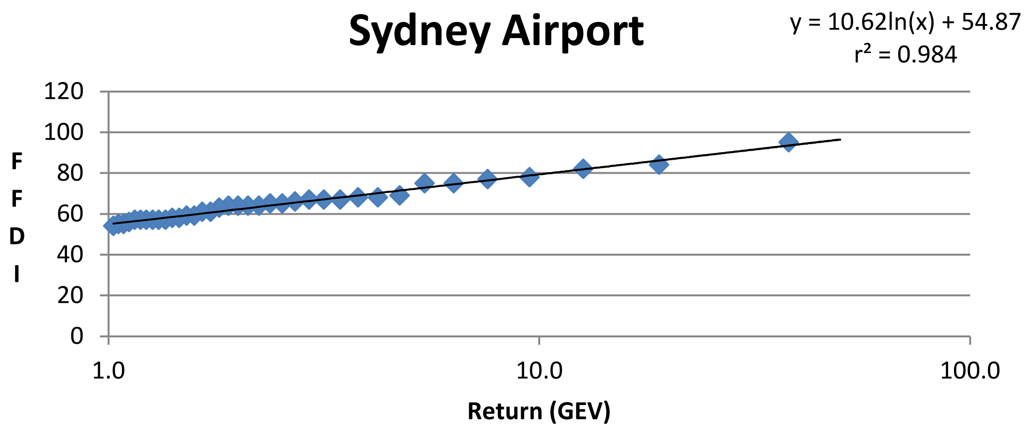


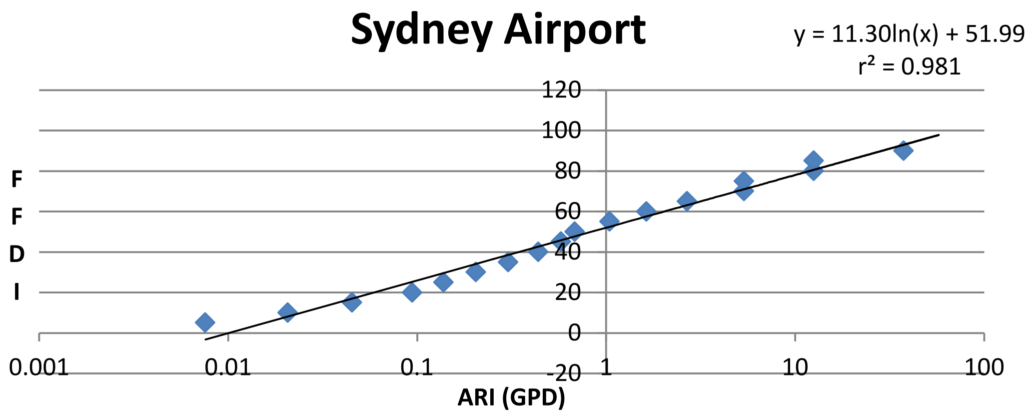


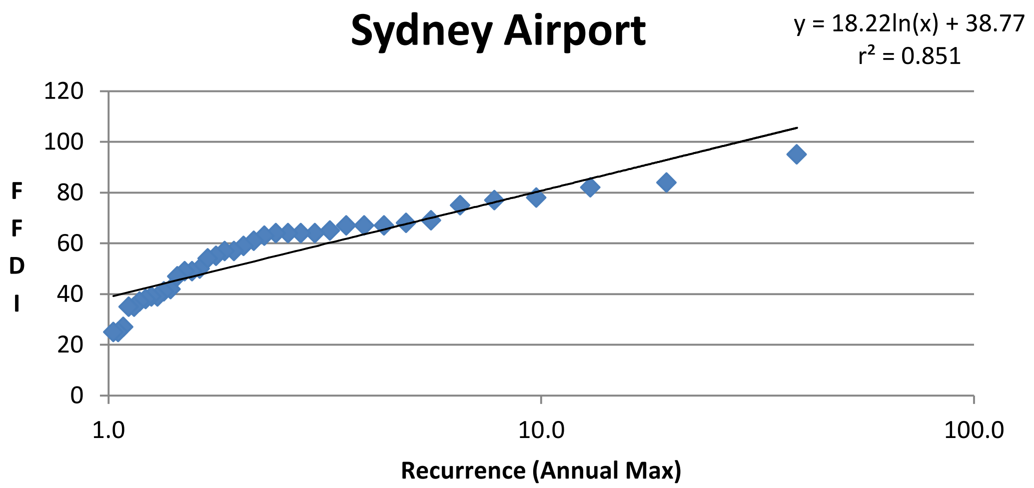


Fire Weather District 4: Greater Sydney.

Weather Station: Sydney Airport (Lucas 2010), Years of data: 37, Highest FFDI Values: 95.

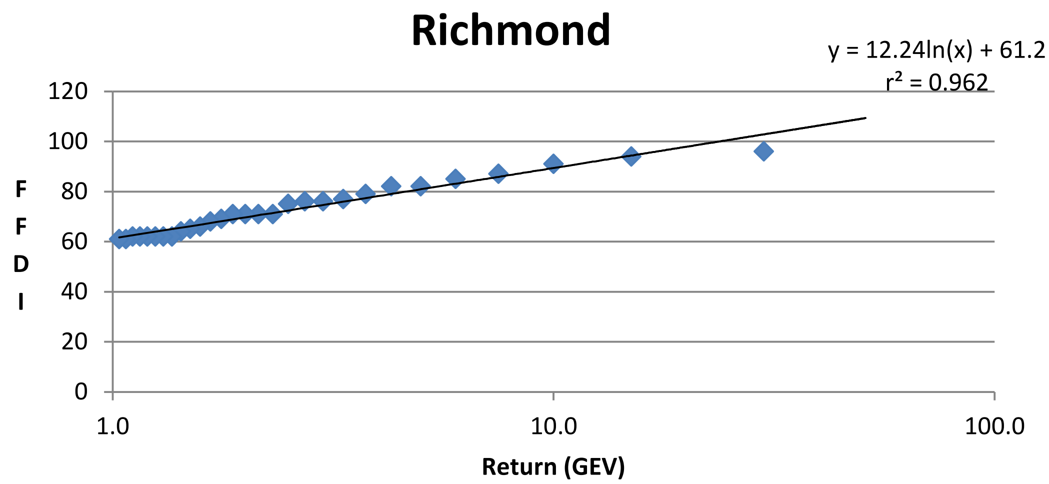


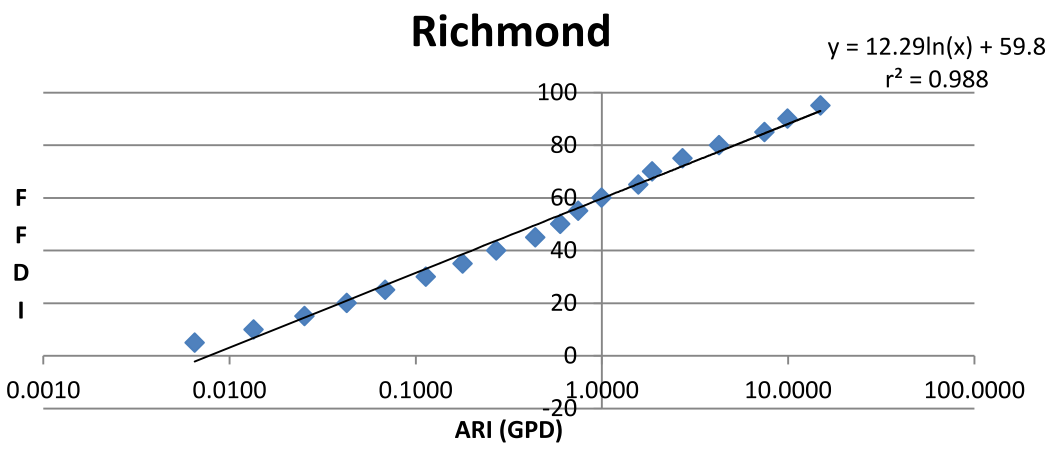


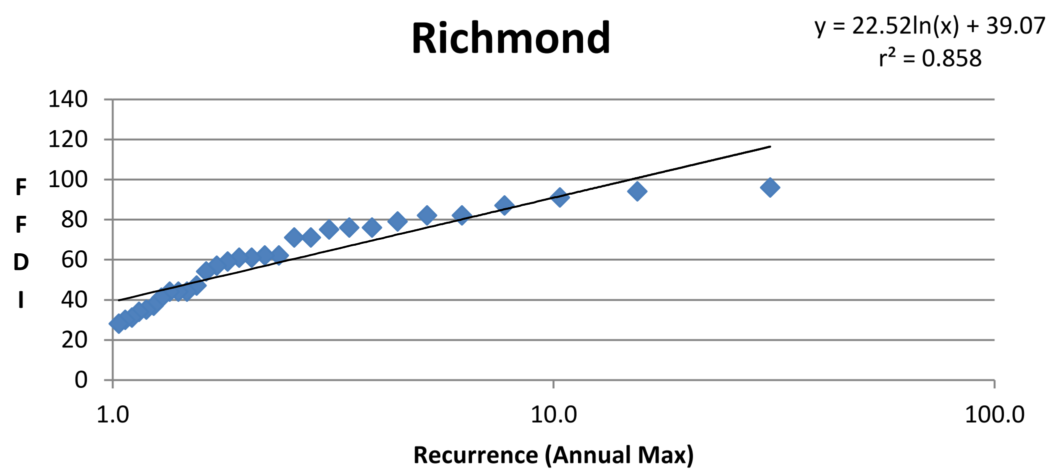


Fire Weather District 4: Greater Sydney.

Weather Station: Richmond Airbase (Lucas 2010), Years of data: 29, Highest FFDI Values: 96.

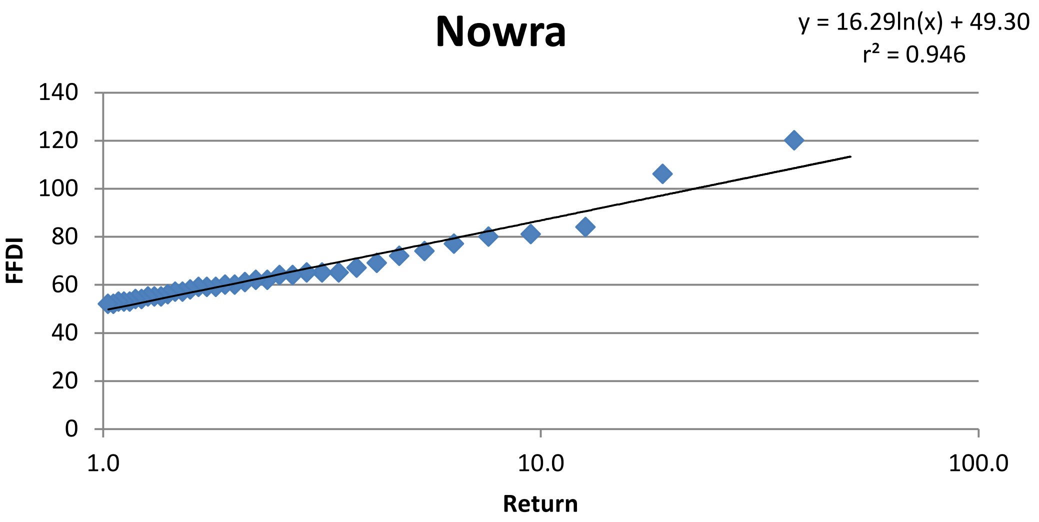


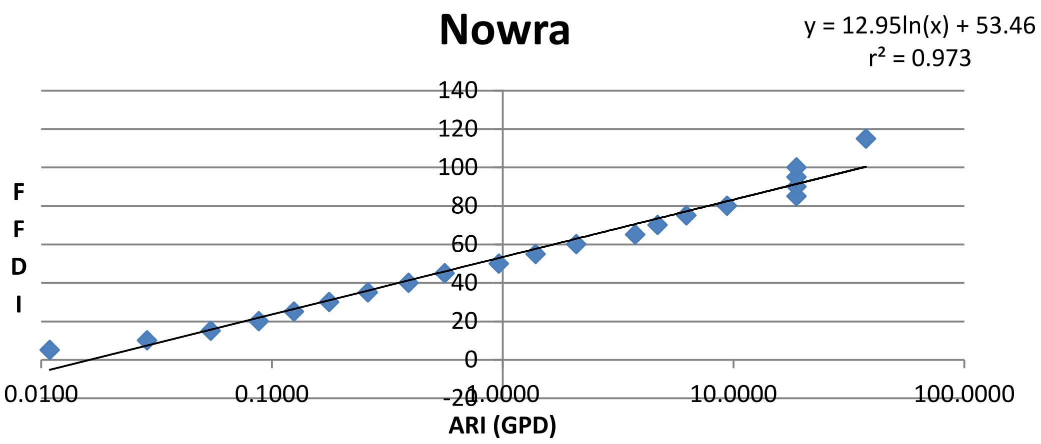


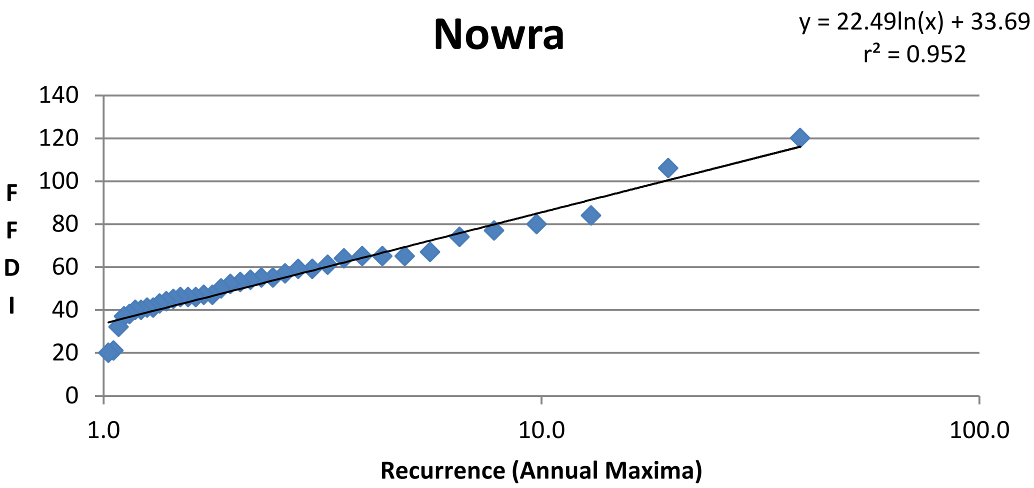


Fire Weather District 5: Illawarra/South Coast.

Weather Station: Nowra (Lucas 2010), Years of data: 37, Highest FFDI Value: 120

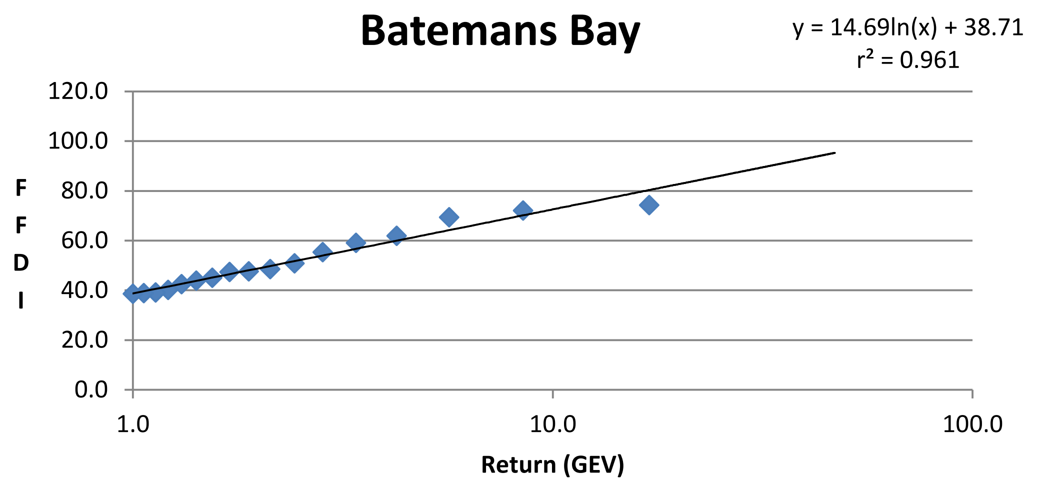


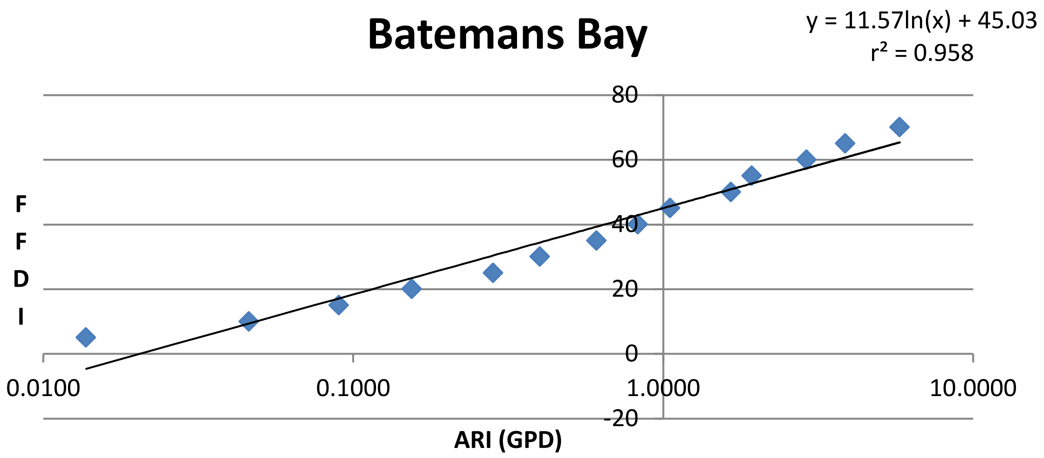


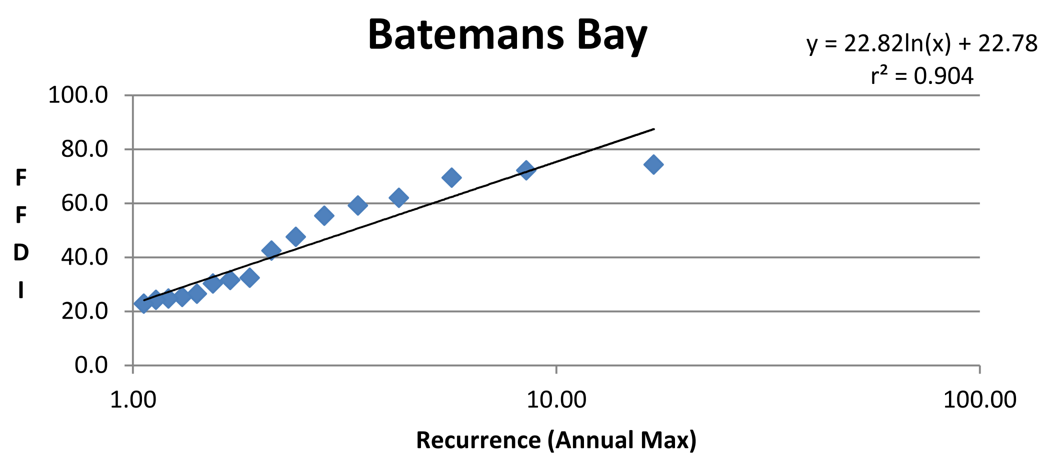


Fire Weather District 6: Far South Coast.

Weather Station: Batemans Bay (BoM derived data), Years of data: 16, Highest FFDI Value: 74

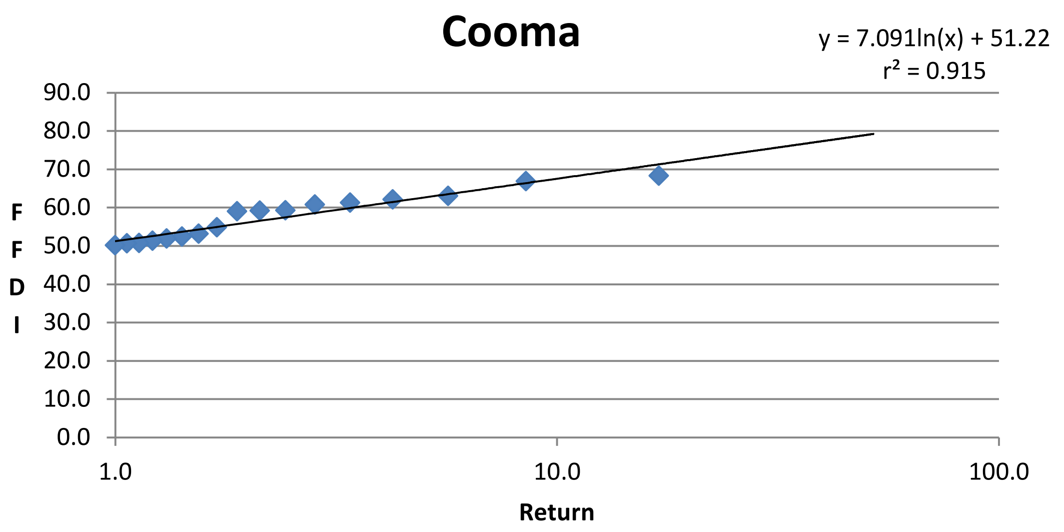


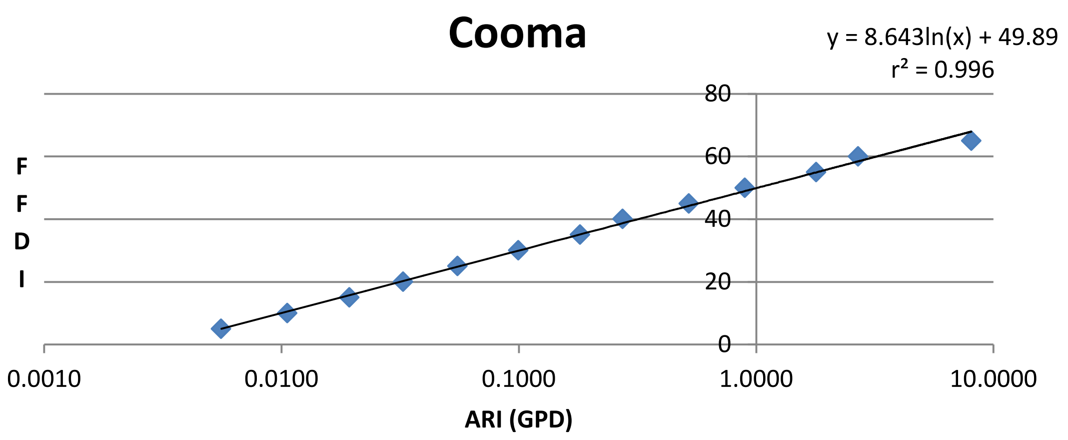


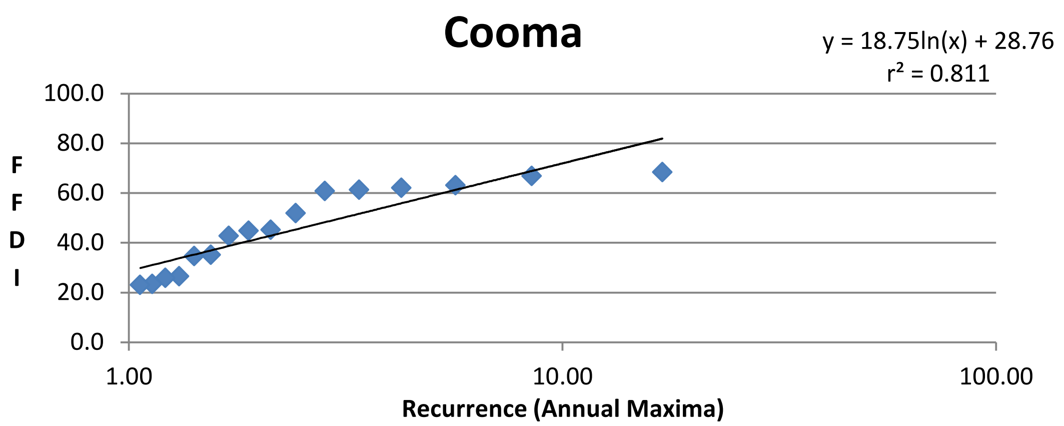


Fire Weather District 7: Monaro Alpine.

Weather Station: Cooma (BoM derived), Years of data: 16, Highest FFDI Value: 68

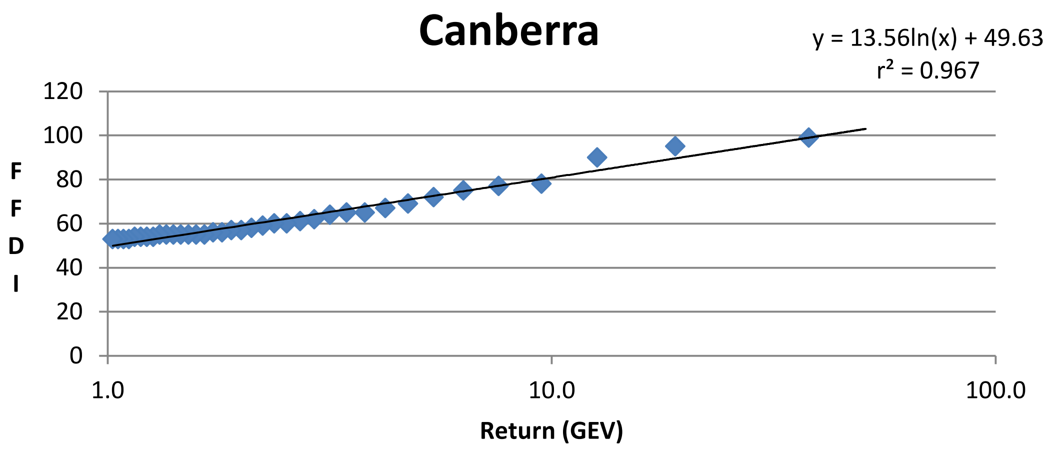


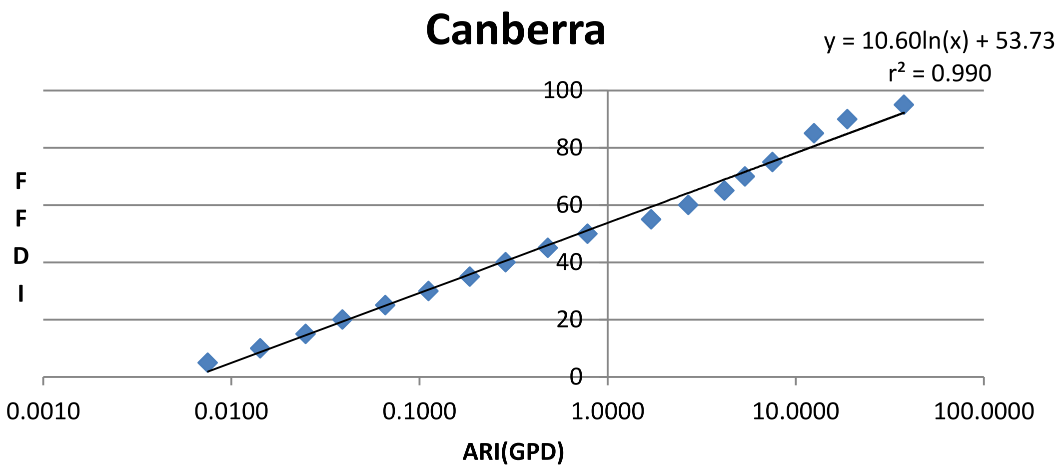


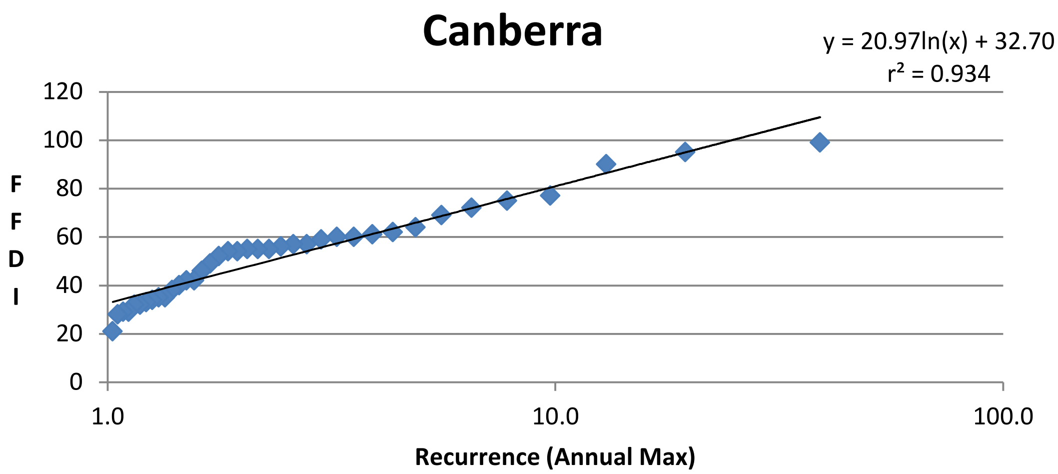


Fire Weather District 8: Australian Capital Territory

Weather Station: Canberra Airport (Lucas, 2010), Years of data: 37, Highest FFDI Value: 99

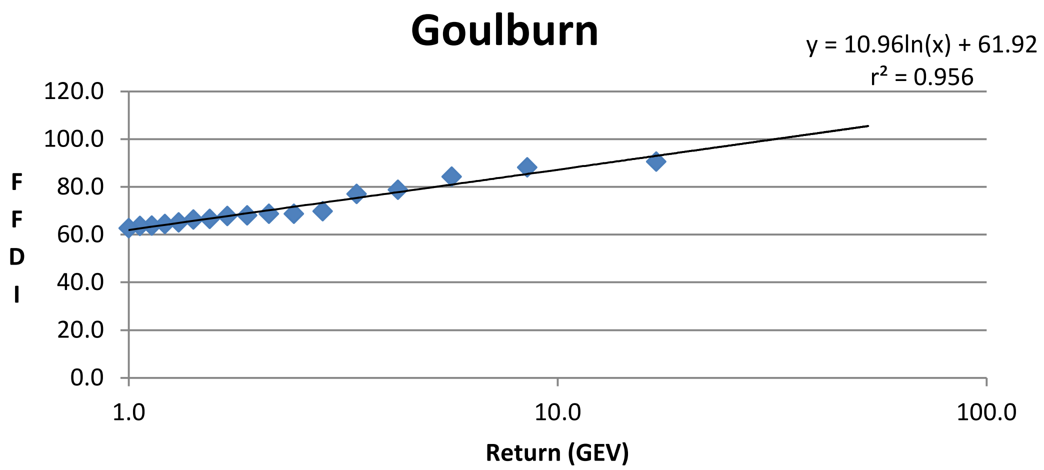


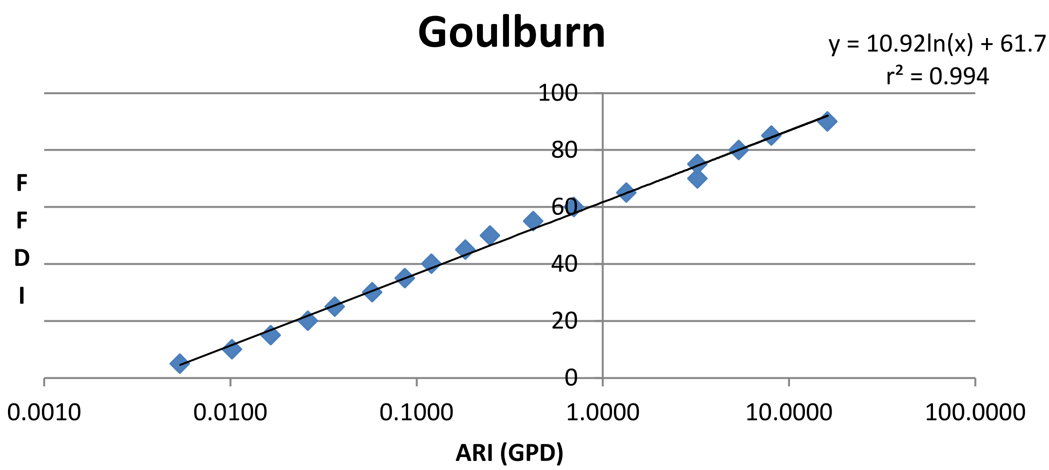


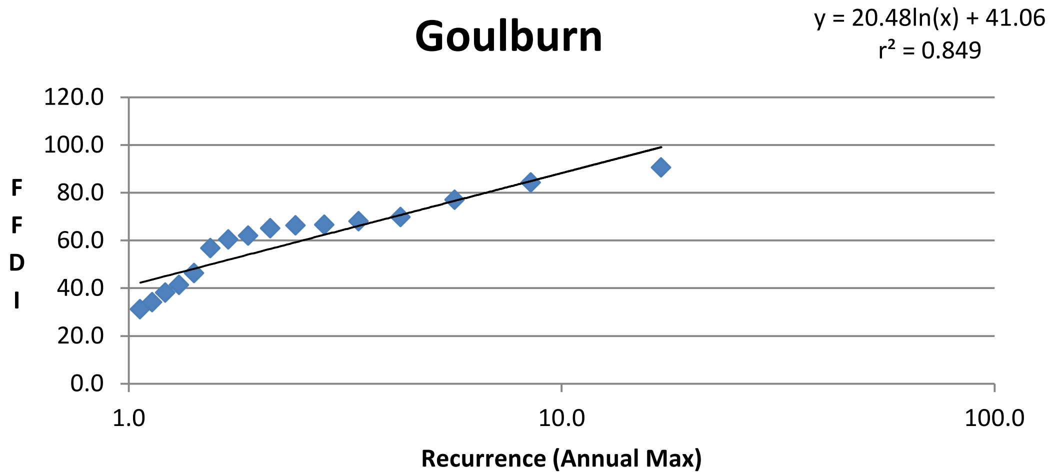


Fire Weather District 9: Southern Ranges.

Weather Station: Goulburn (BoM derived data), Years of data: 16, Highest FFDI Value: 91

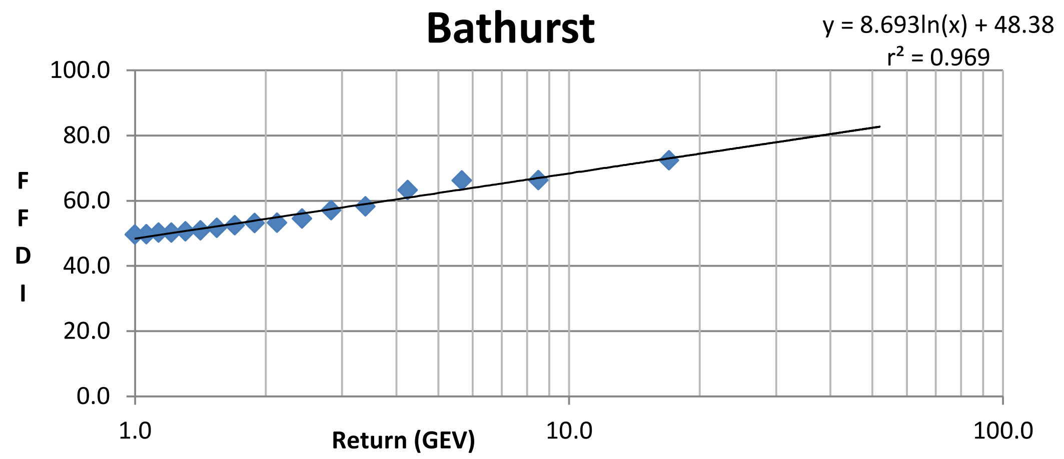


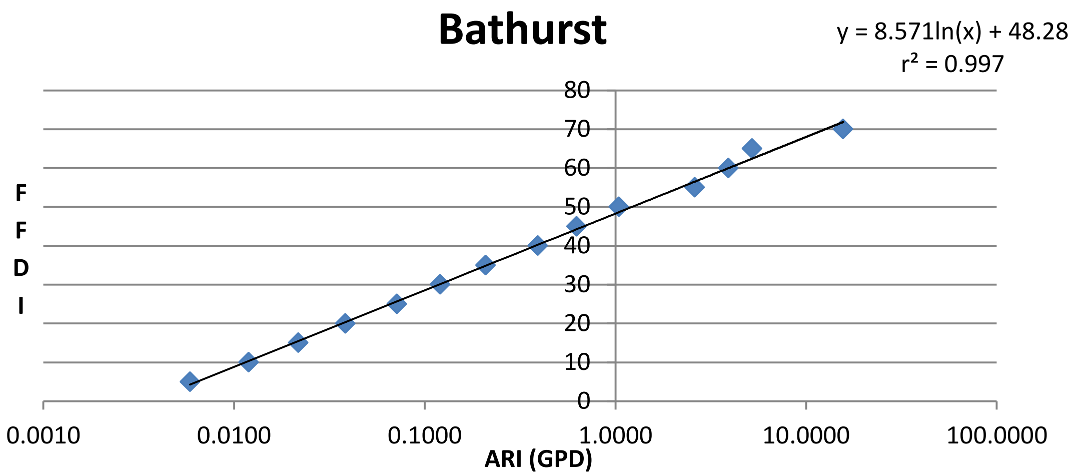


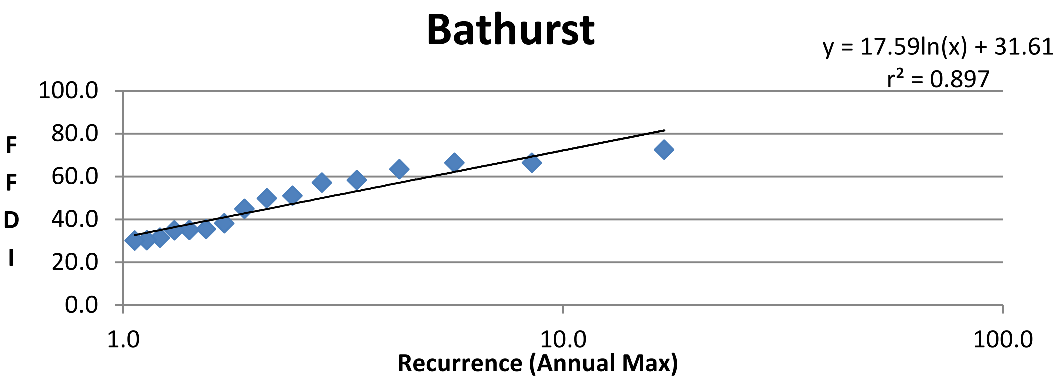


Fire Weather District 10: Central Ranges.

Weather Station: Bathurst (BoM derived data), Years of data: 16, Highest FFDI Value: 91

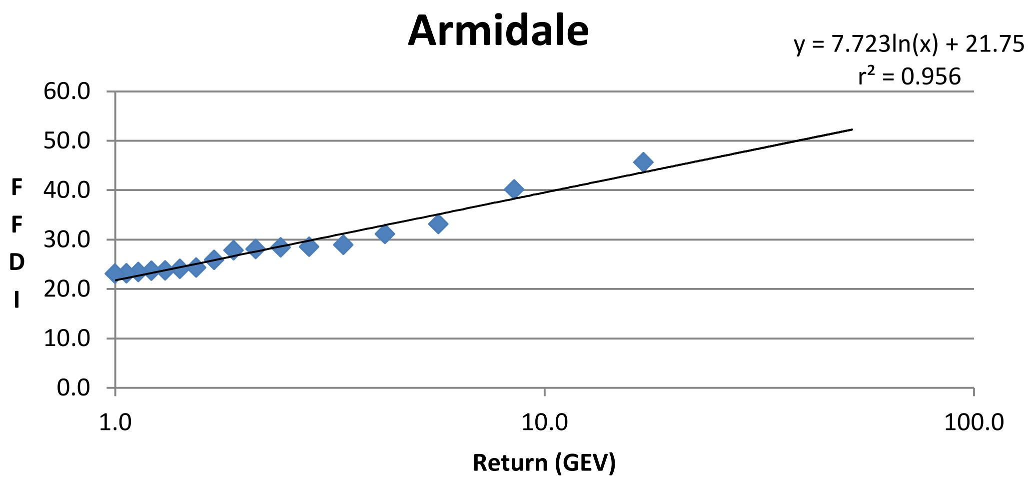


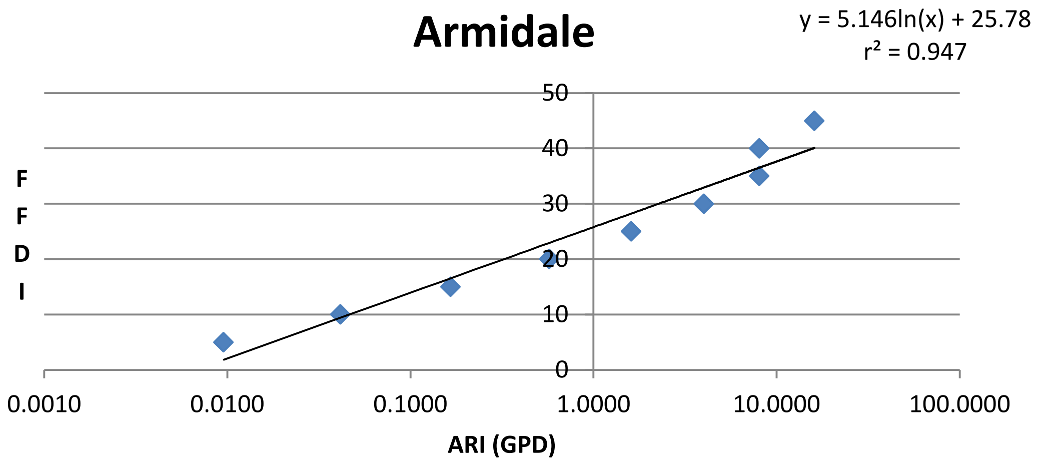


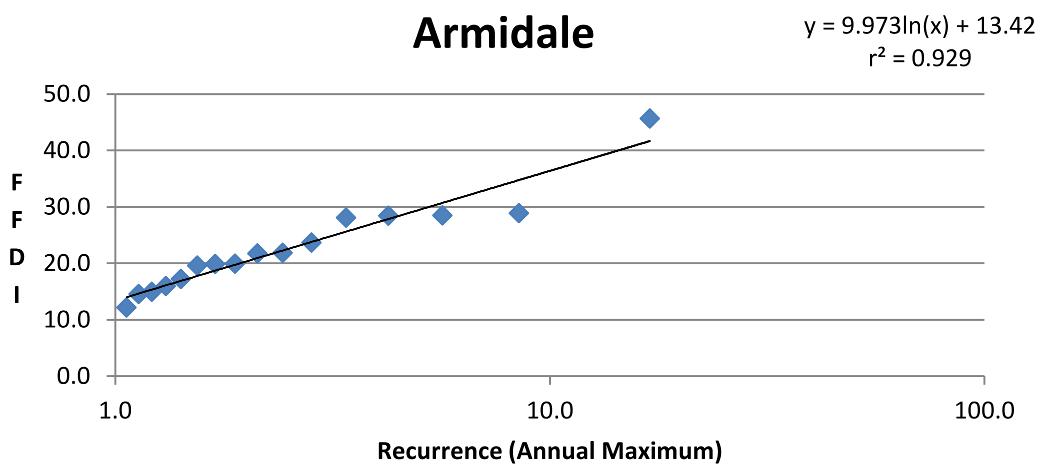


Fire Weather District 11: New England.

Weather Station: Armidale (BoM derived data), Years of data: 16, Highest FFDI Value: 46

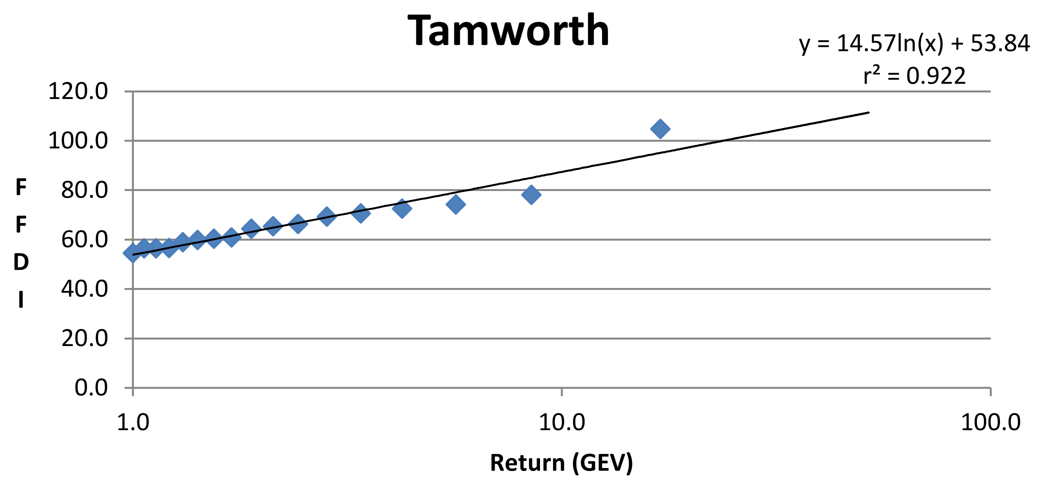


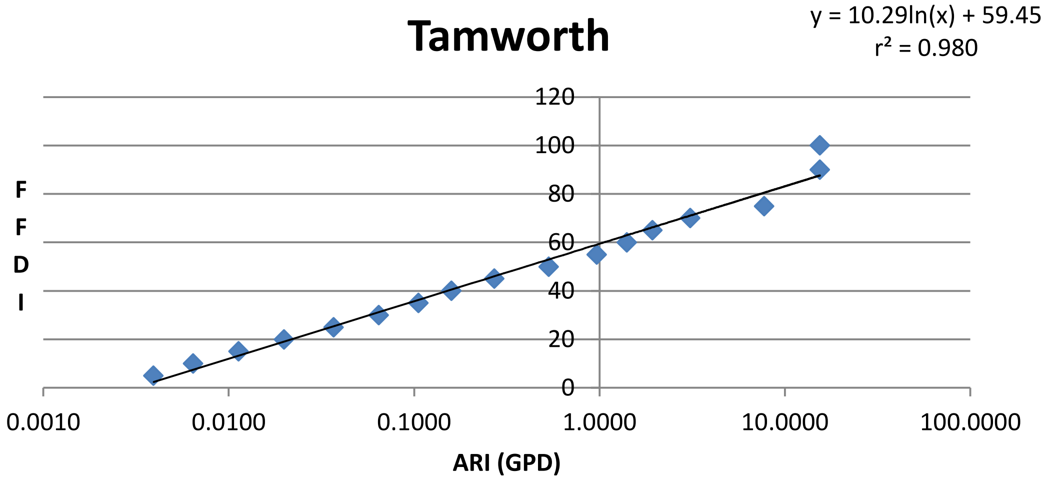


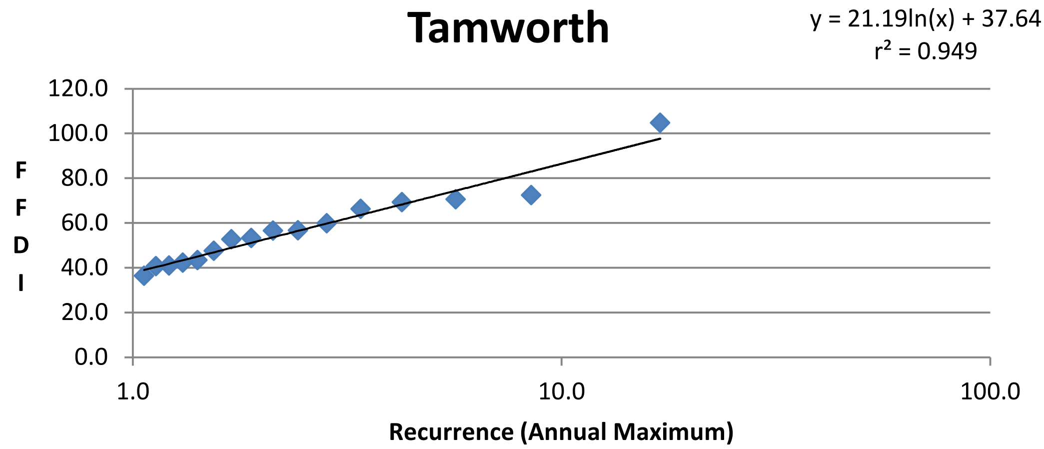


Fire Weather District 12: Northern Slopes.

Weather Station: Tamworth (BoM derived data), Years of data: 16, Highest FFDI Value: 105

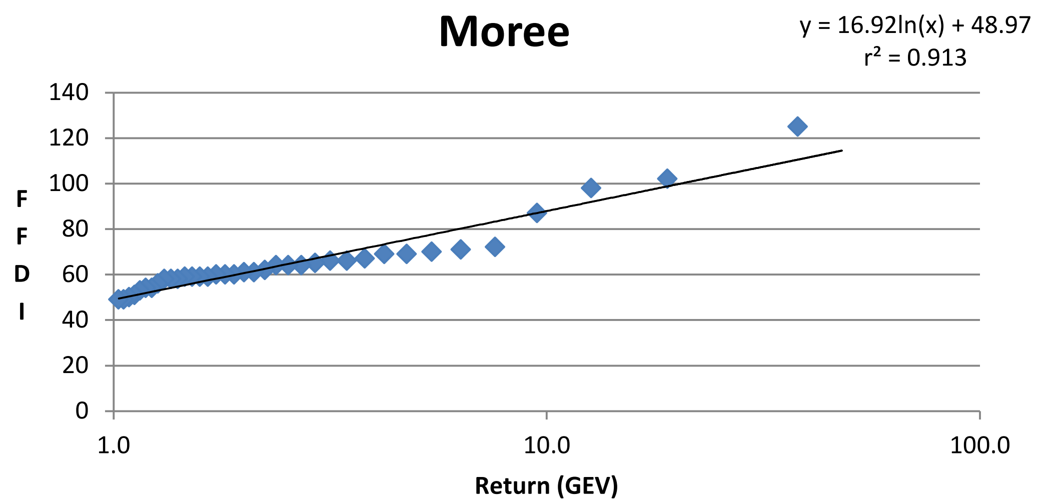


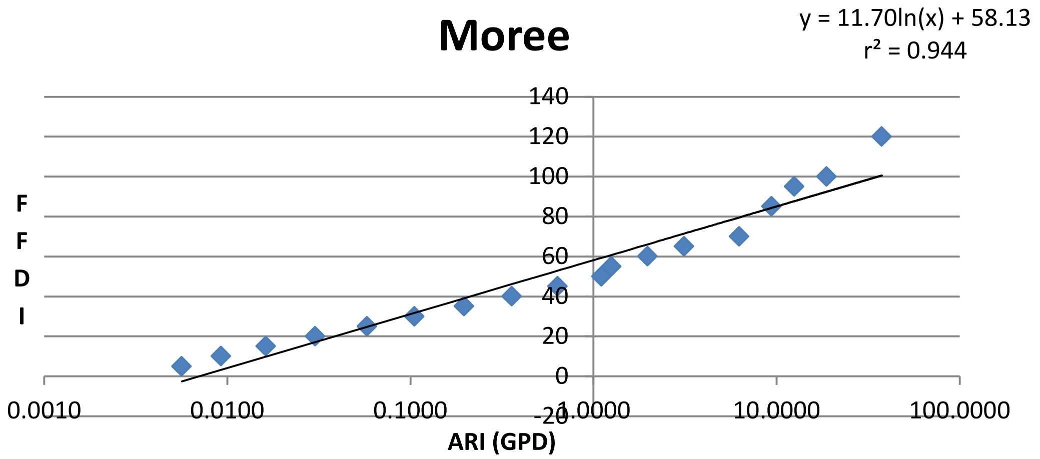


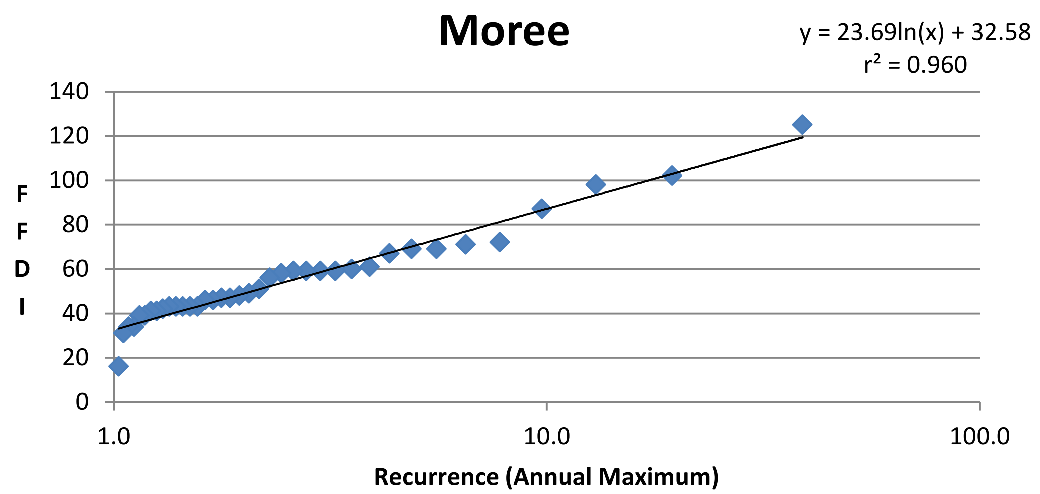


Fire Weather District 13: North Western.

Weather Station: Moree (Lucas, 2010), Years of data: 37, Highest FFDI Value: 125

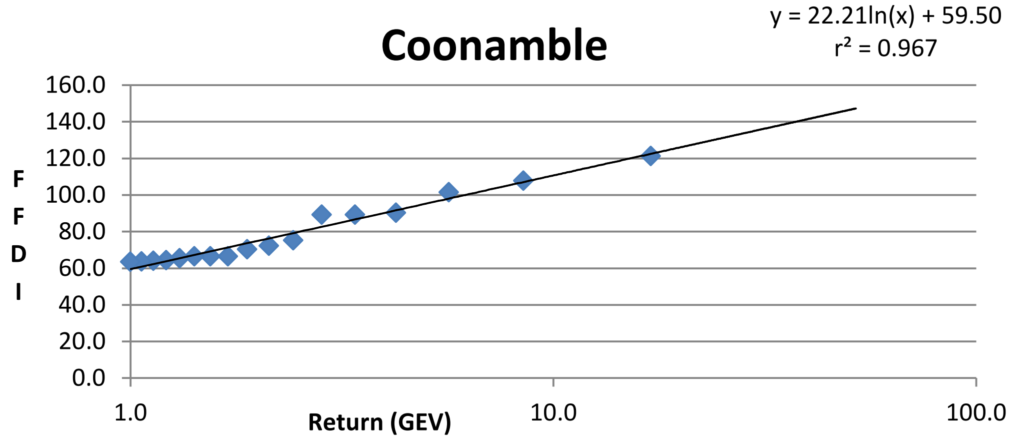


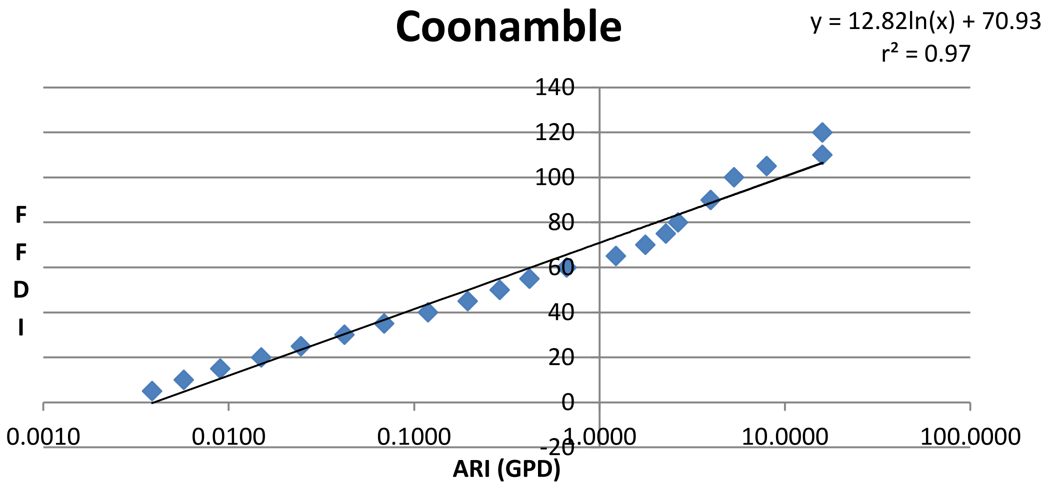


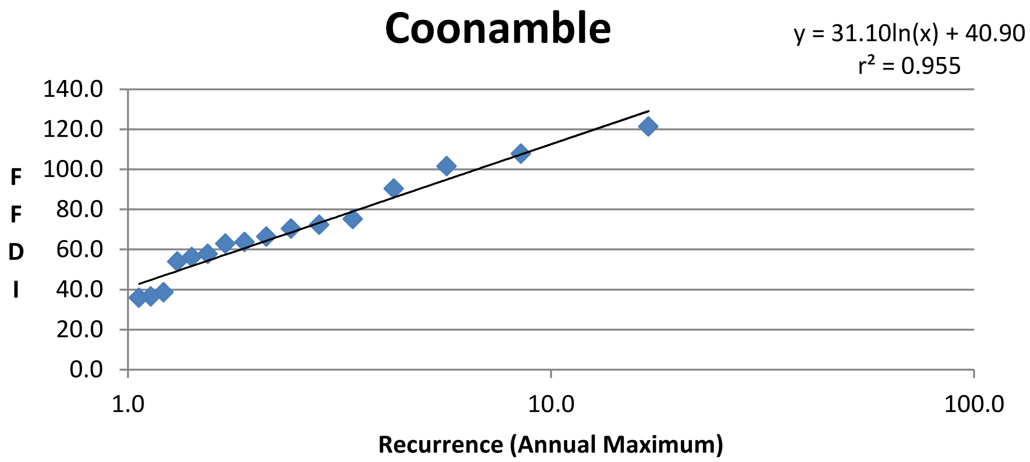


Fire Weather District 14: Upper Central West Plains.

Weather Station: Coonamble (BoM, derived data), Years of data: 16, Highest FFDI Value: 121

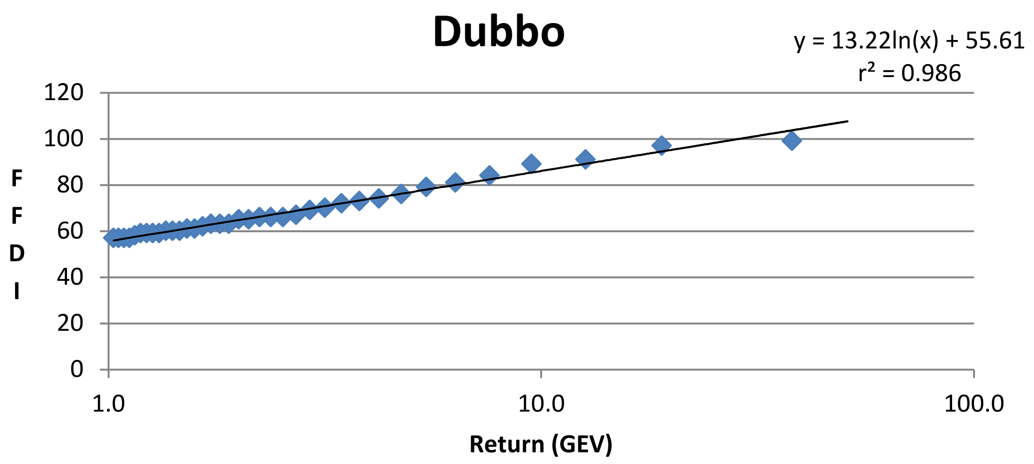


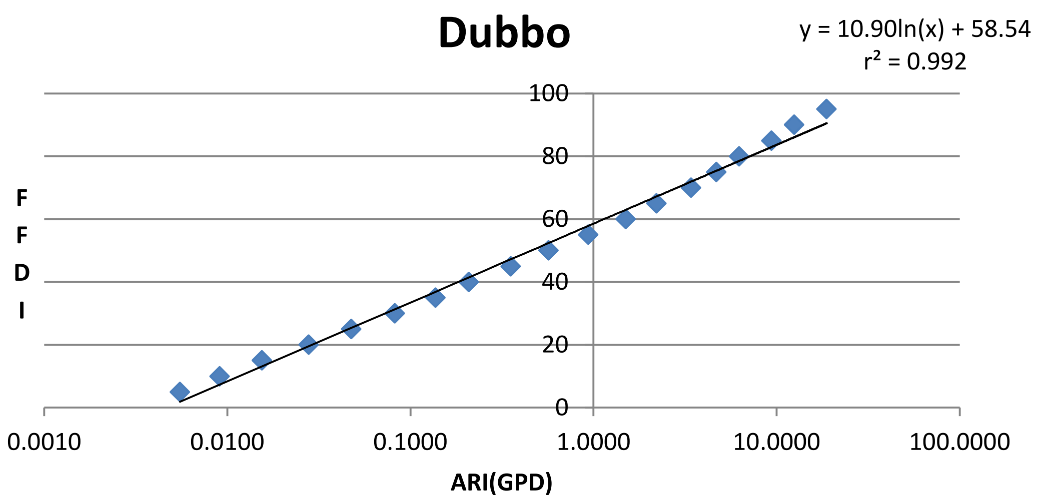


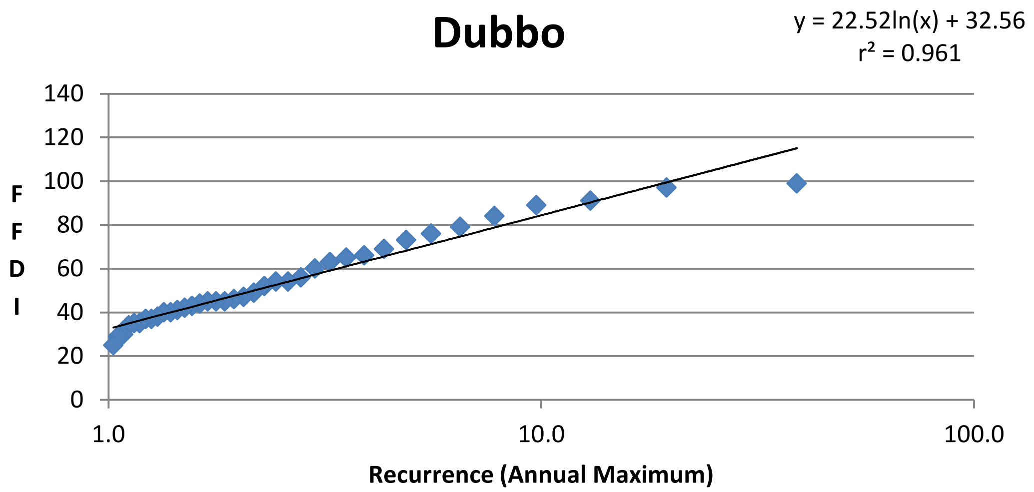


Fire Weather District 15: Lower Central West Plains.

Weather Station: Dubbo (Lucas, 2010), Years of data: 37, Highest FFDI Value: 99

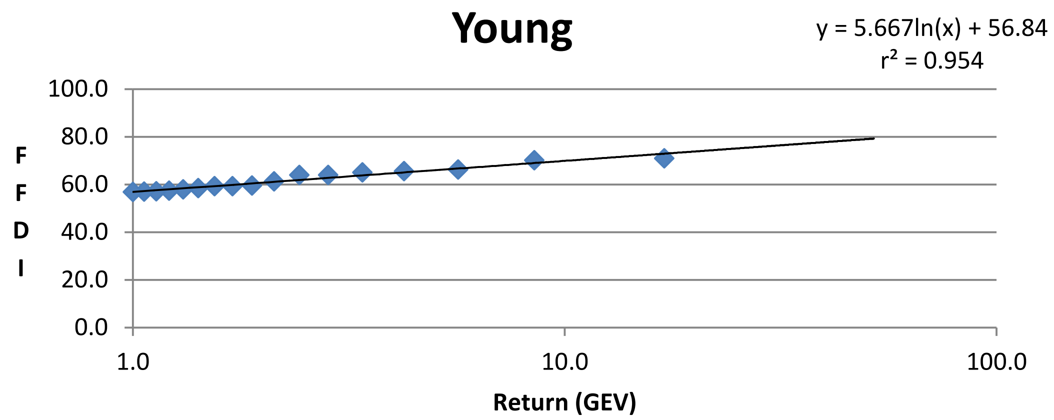


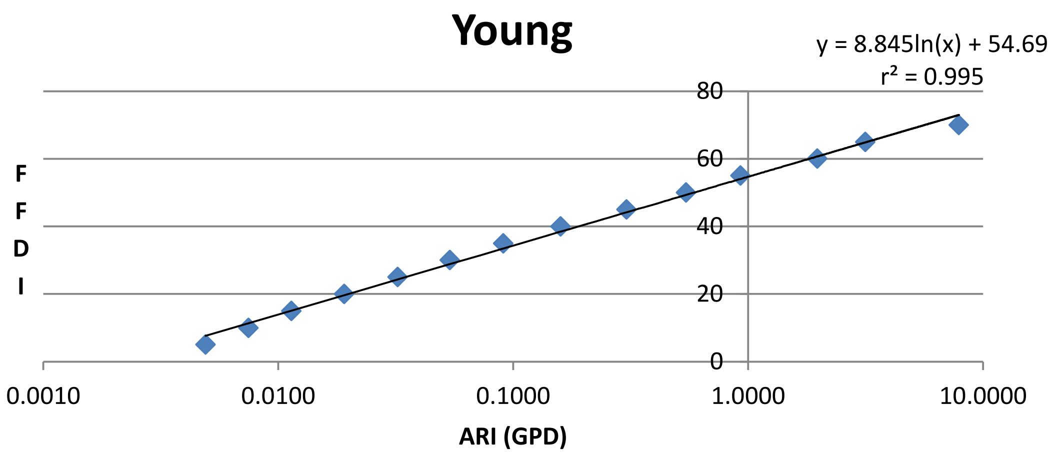


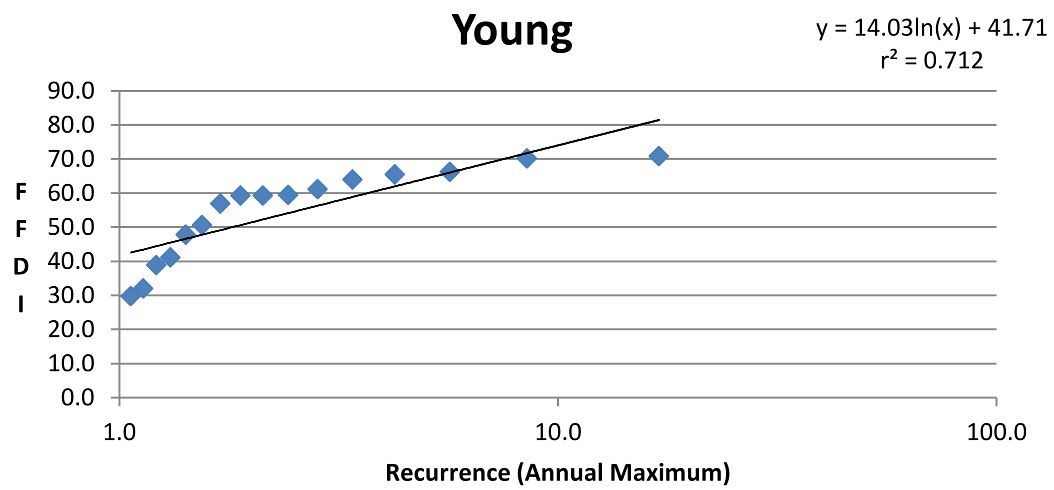


Fire Weather District 16: Southern Slopes.

Weather Station: Young (BoM derived data), Years of data: 16, Highest FFDI Value: 71

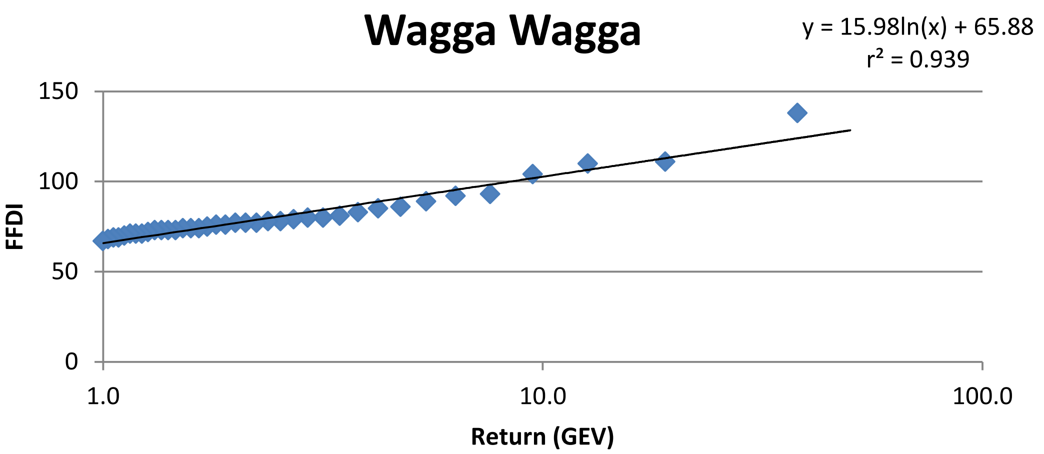


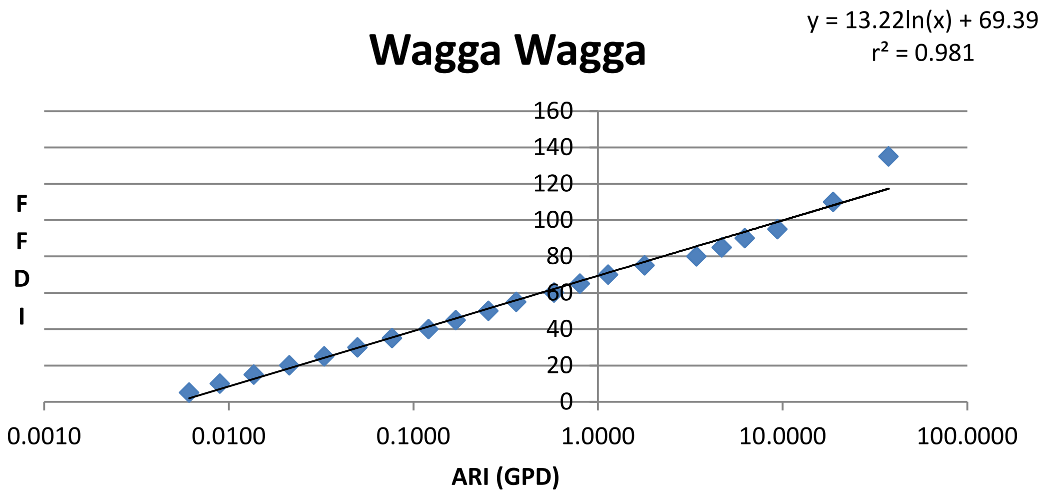


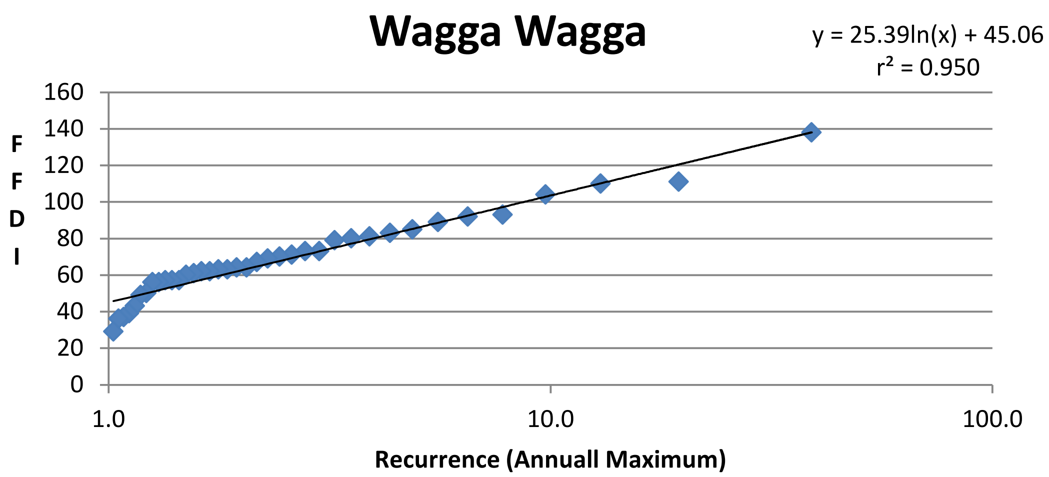


Fire Weather District 17: Eastern Riverina.

Weather Station: Wagga Wagga (Lucas 2010), Years of data: 37, Highest FFDI Value: 138

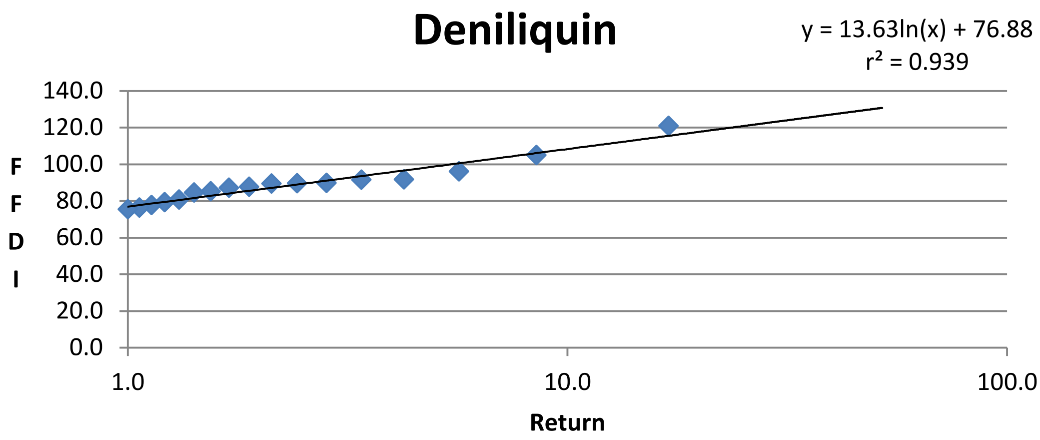


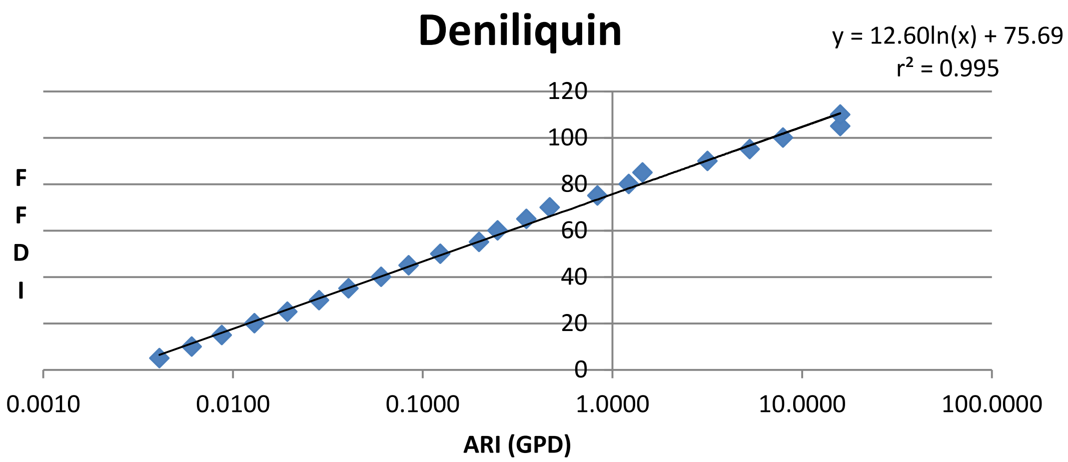


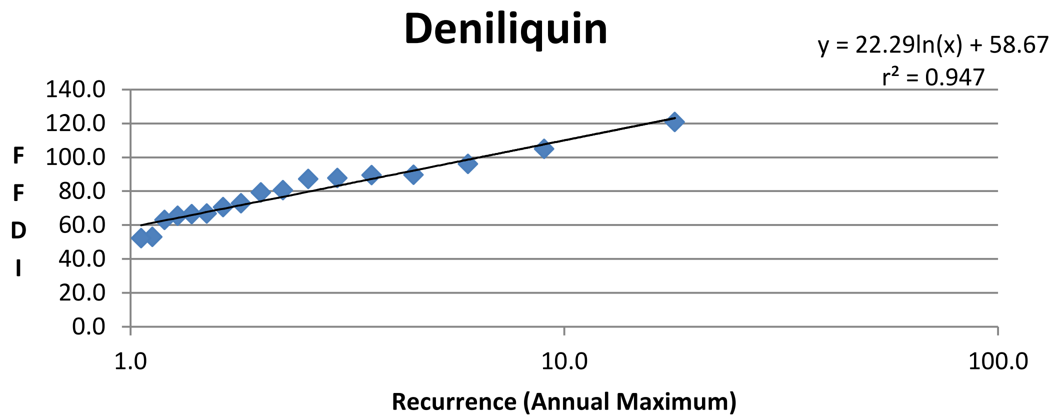


Fire Weather District 18: Southern Riverina.

Weather Station: Deniliquin (BoM derived data), Years of data: 16, Highest FFDI Value: 121

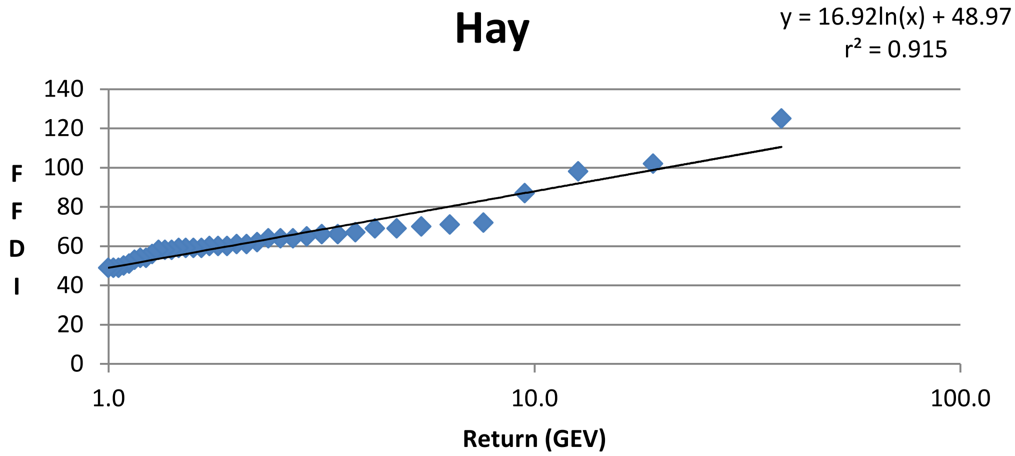


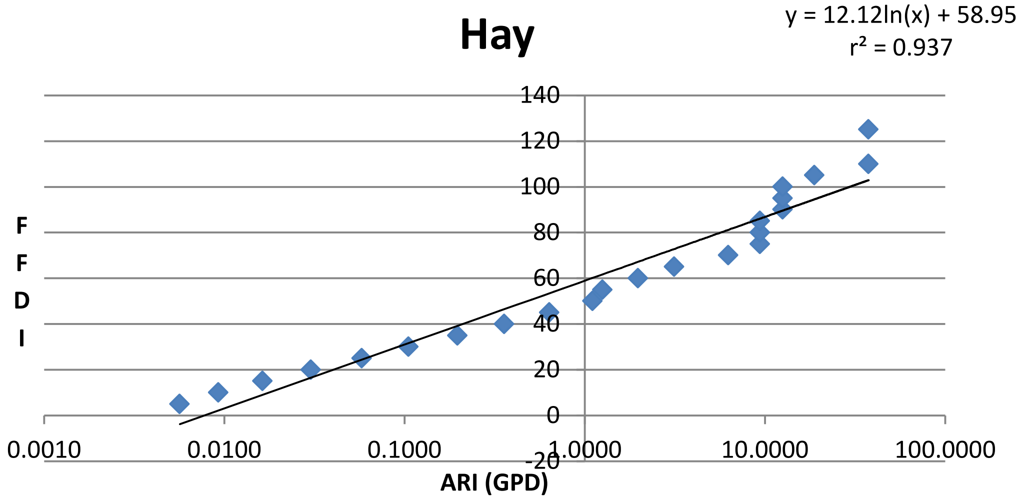


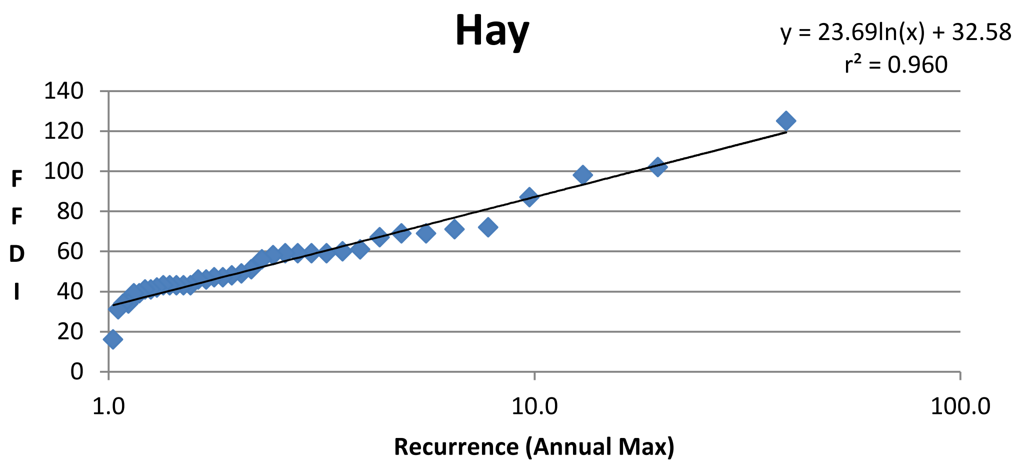


Fire Weather District 19: Northern Riverina.

Weather Station: Hay (BoM derived data), Years of data: 37, Highest FFDI Value: 125

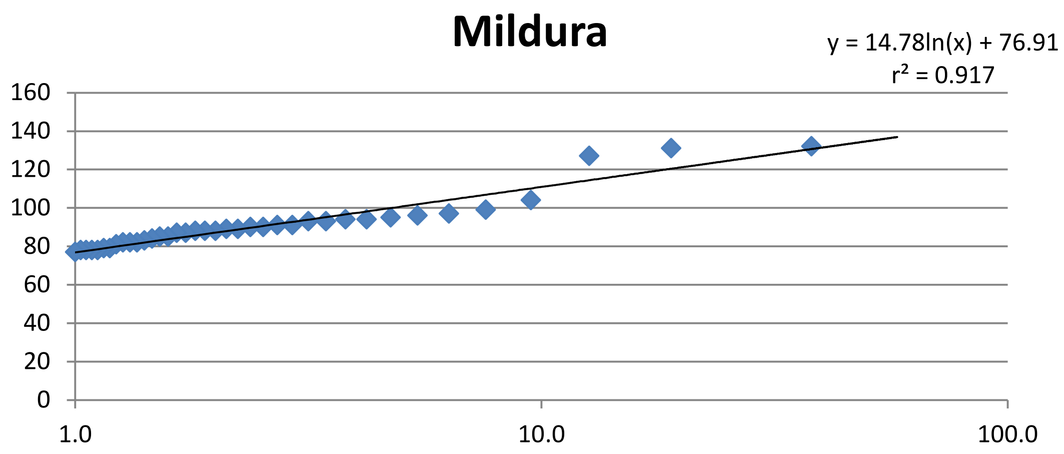


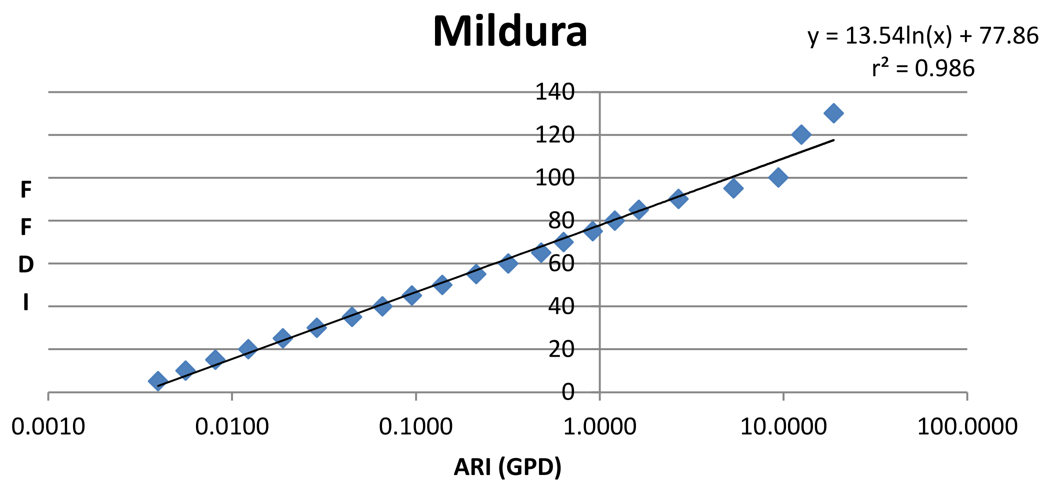


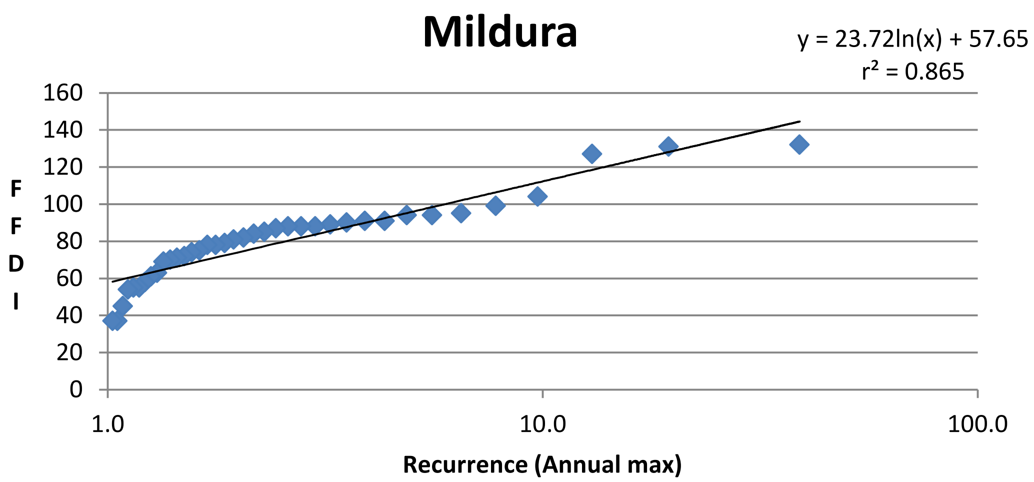


Fire Weather District 20: South Western.

Weather Station: Mildura (Lucas 2010), Years of data: 37, Highest FFDI Value: 132

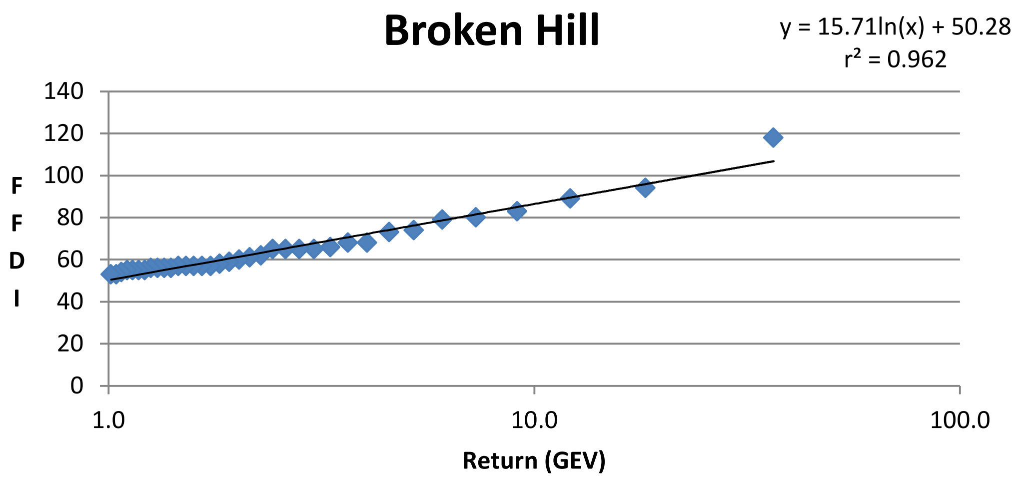


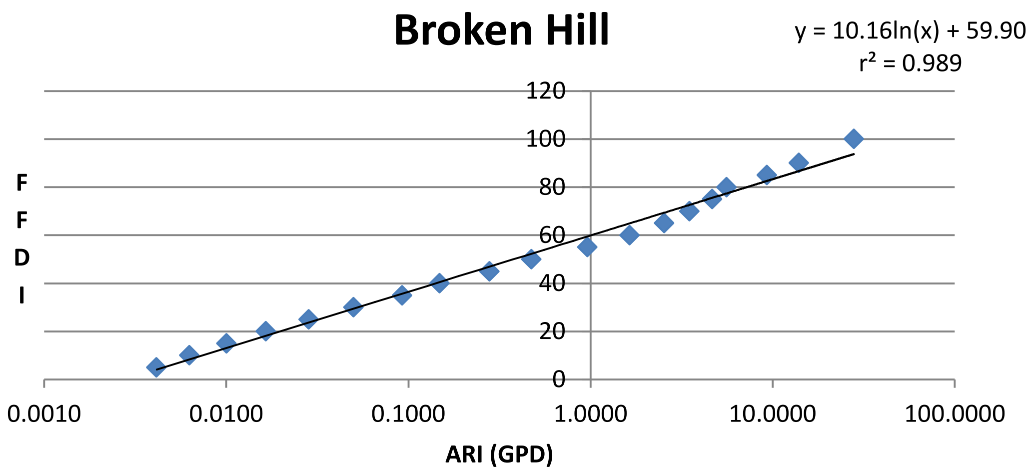


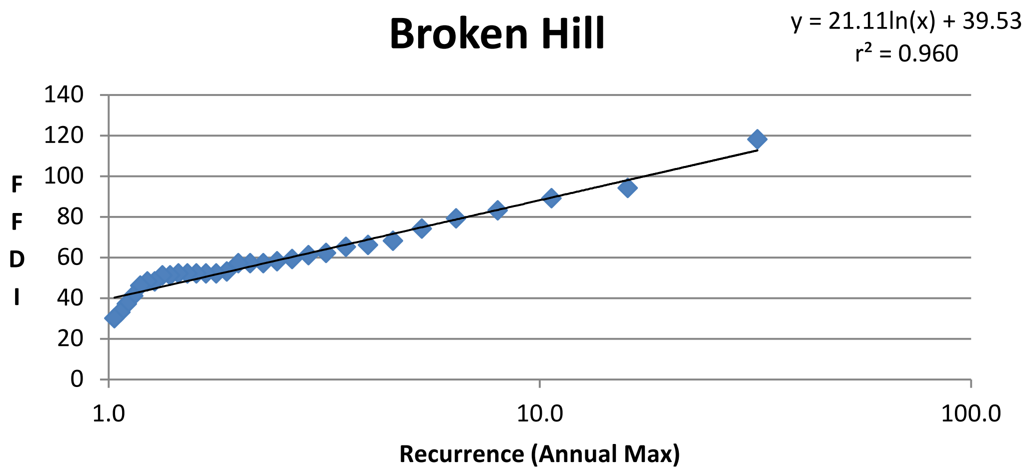


Fire Weather District 21: Far Western.

Weather Station: Broken Hill (Lucas, 2010), Years of data: 35.5, Highest FFDI Value: 118

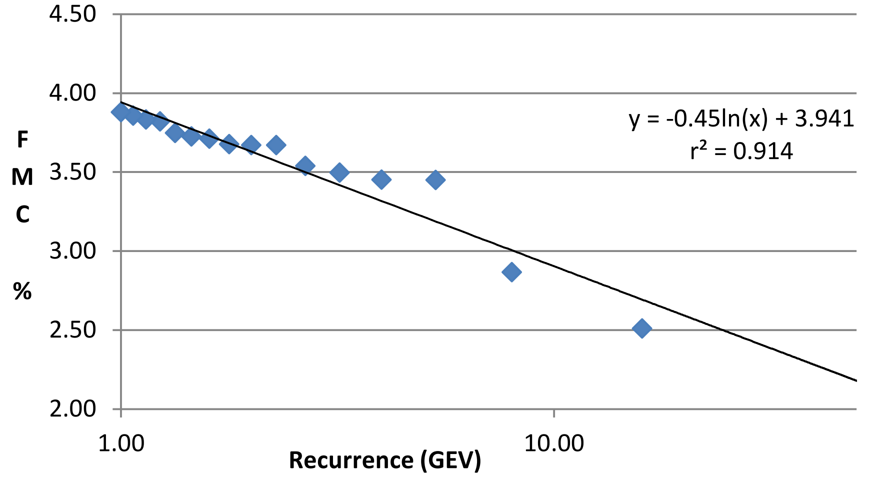




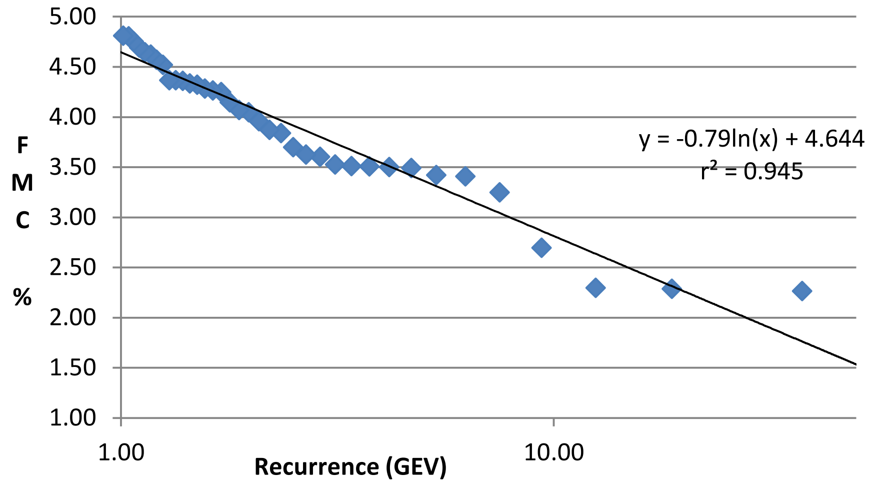


APPENDIX 6 - GEV_{50} Fuel Moisture Curves for NSW

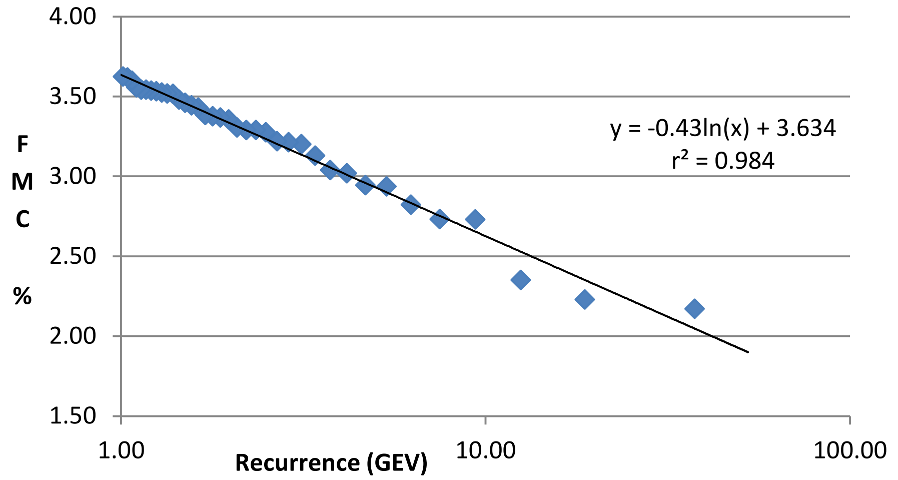
Fire Weather District: 1. Far North Coast (Grafton).



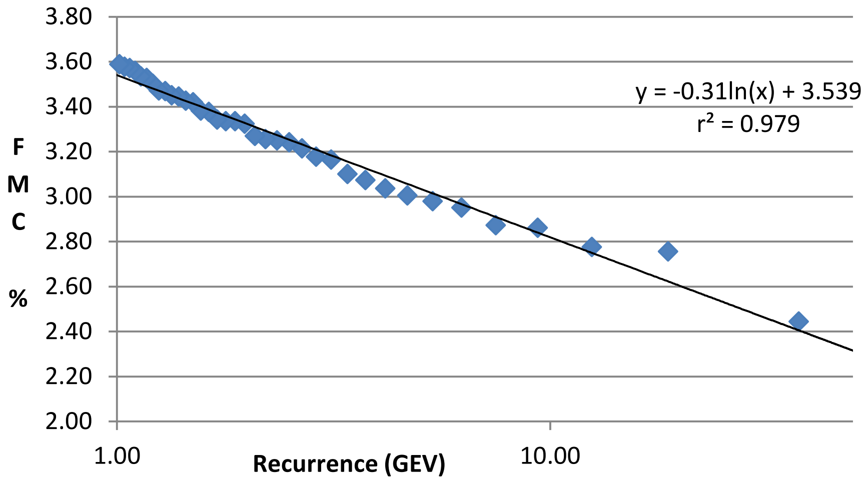
Fire Weather District : 2. North Coast (Coffs Harbour)



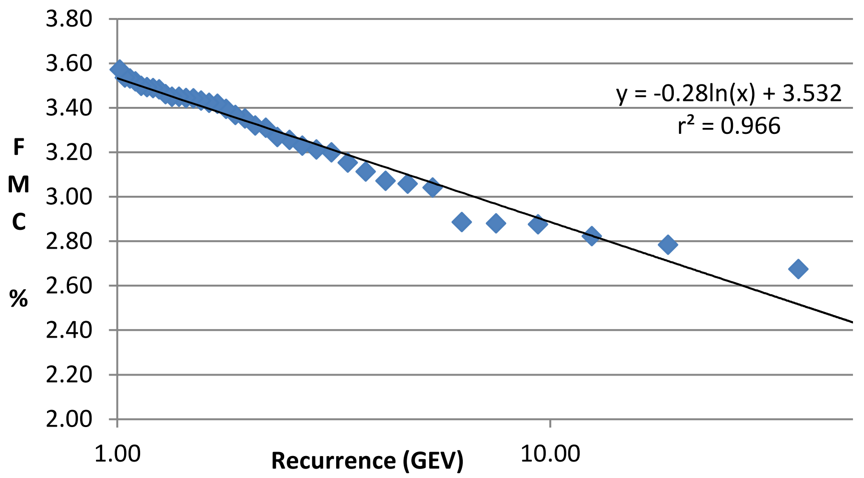
Fire Weather District: 3. Greater Hunter (Williamtown).



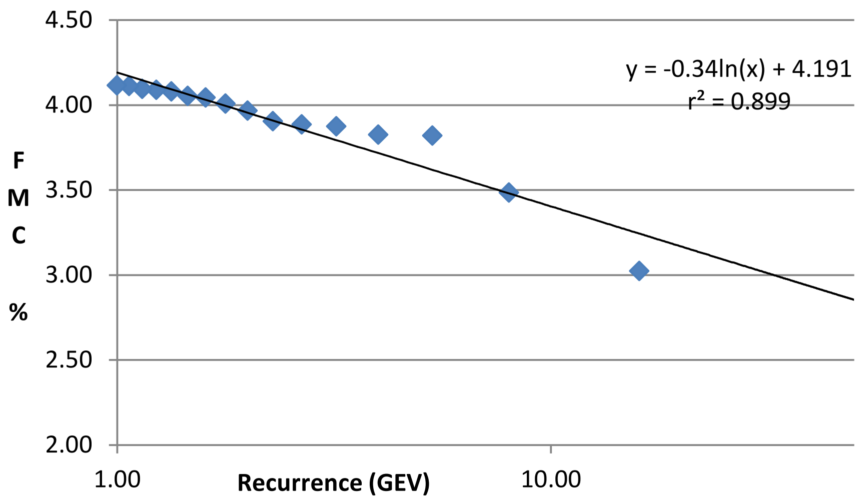
Fire Weather District: 4. Greater Sydney (Sydney Airport).



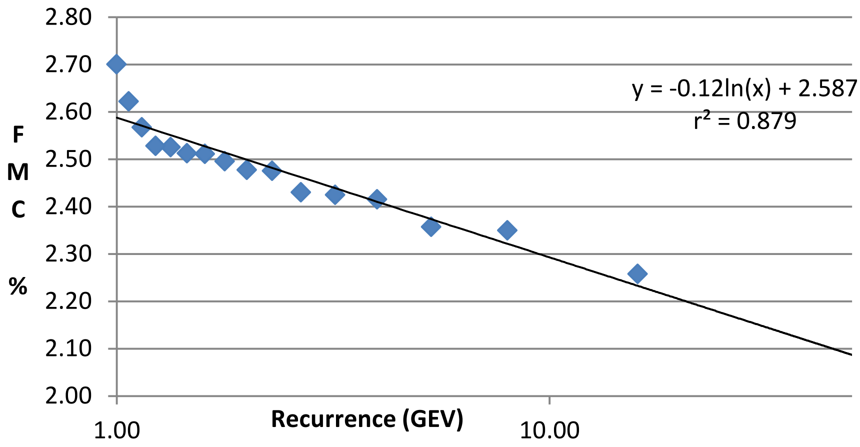
Fire Weather District: 5. Illawarra/South Coast (Nowra).



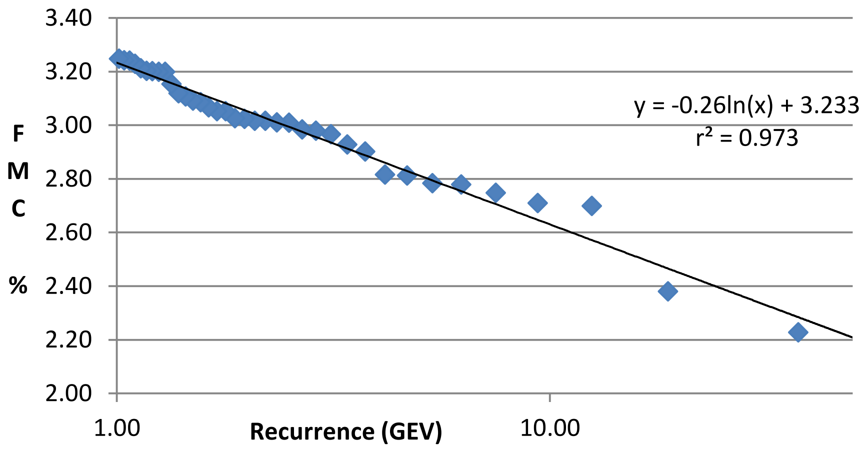
Fire Weather District: 6. Far South Coast (Batemans Bay).



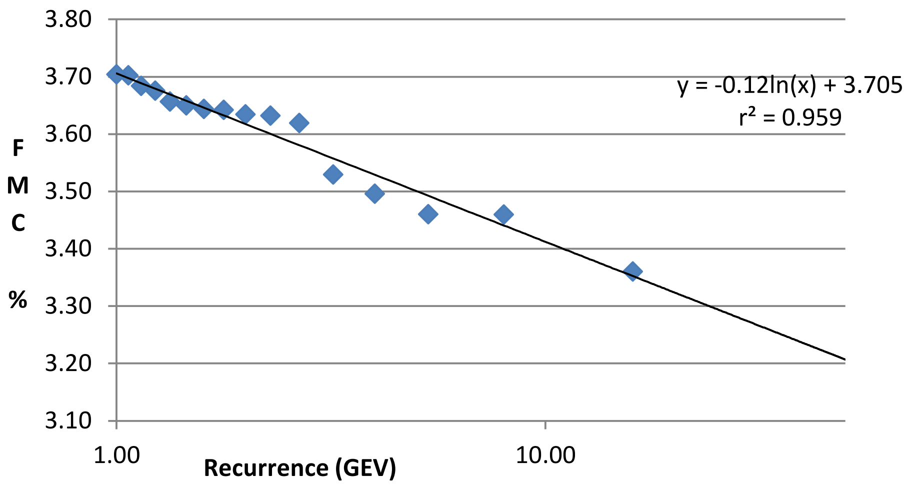
Fire Weather District: 7. Monaro-Alpine (Cooma).



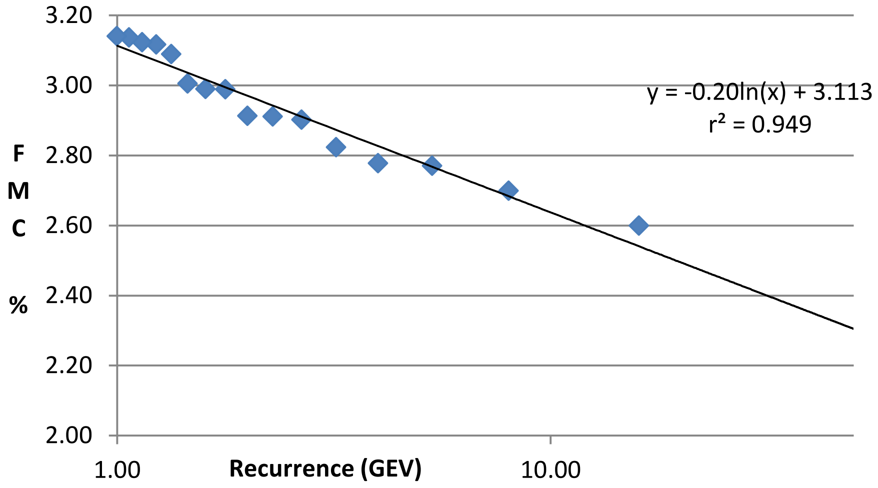
Fire Weather District: 8. Australian Capital Territory (Canberra Airport)



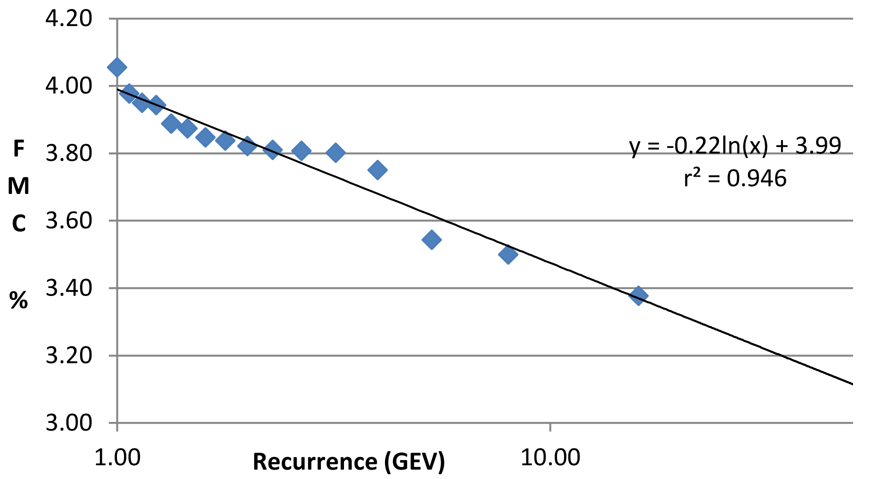
Fire Weather District: 9. Southern Tablelands (Goulburn).



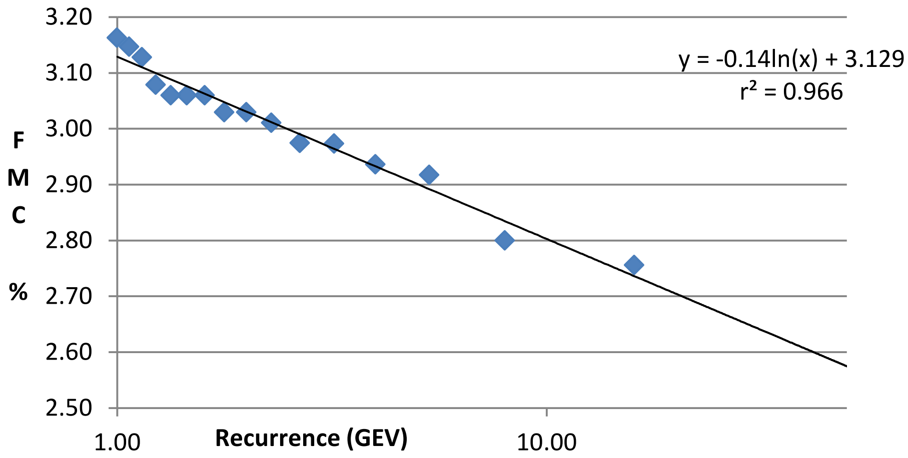
Fire Weather District: 10. Central Tablelands (Bathurst).



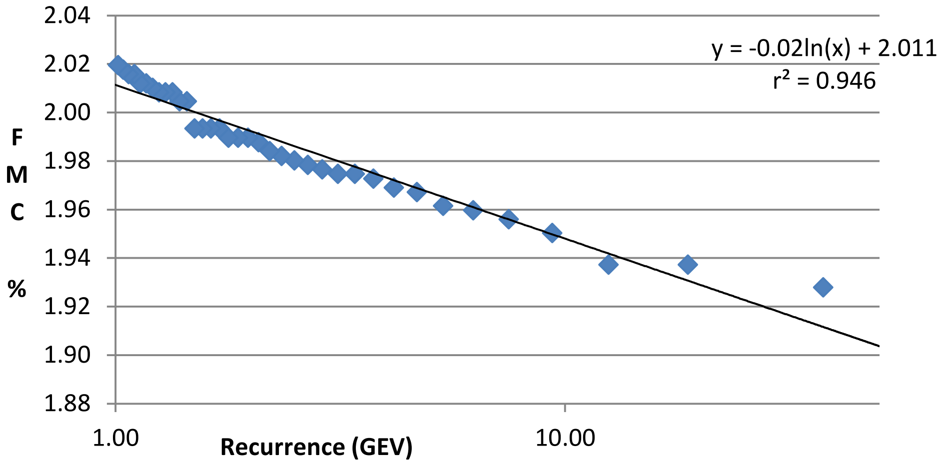
Fire Weather District: 11. New England (Armidale).



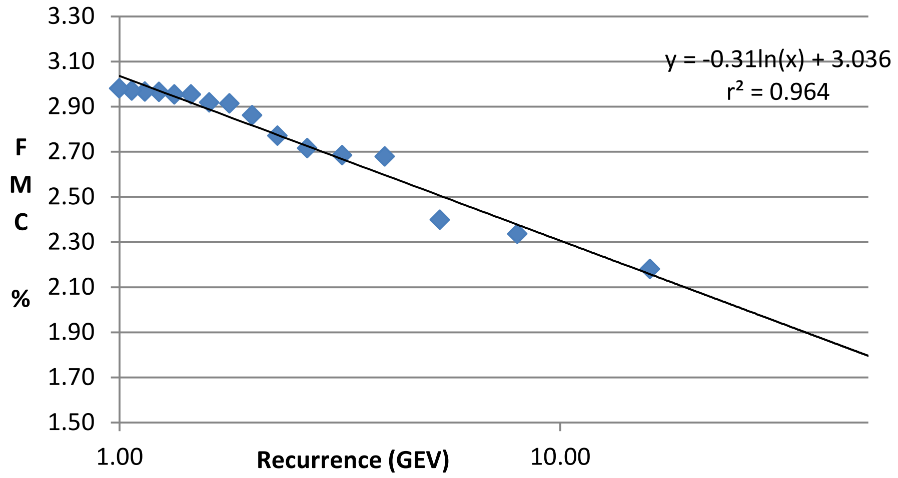
Fire Weather District: 12. Northern Ranges (Tamworth).



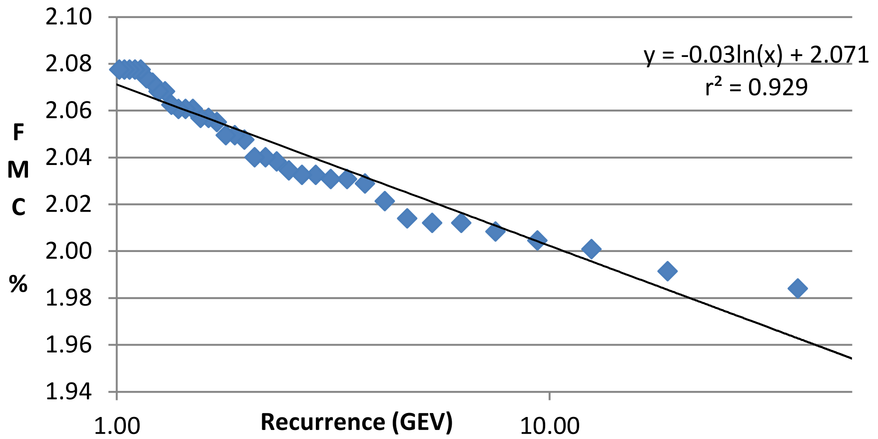
Fire Weather District: 13. North-Western (Moree).



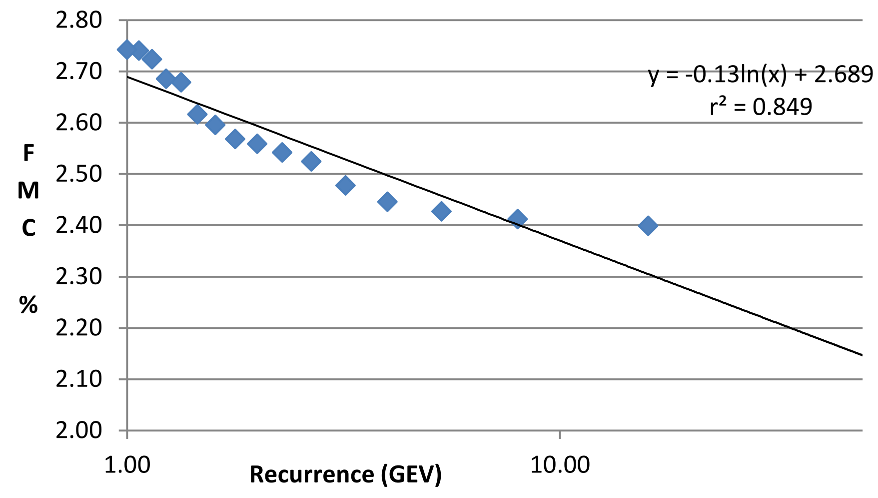
Fire Weather District: 14: Upper Central Western Plains (Coonamble).



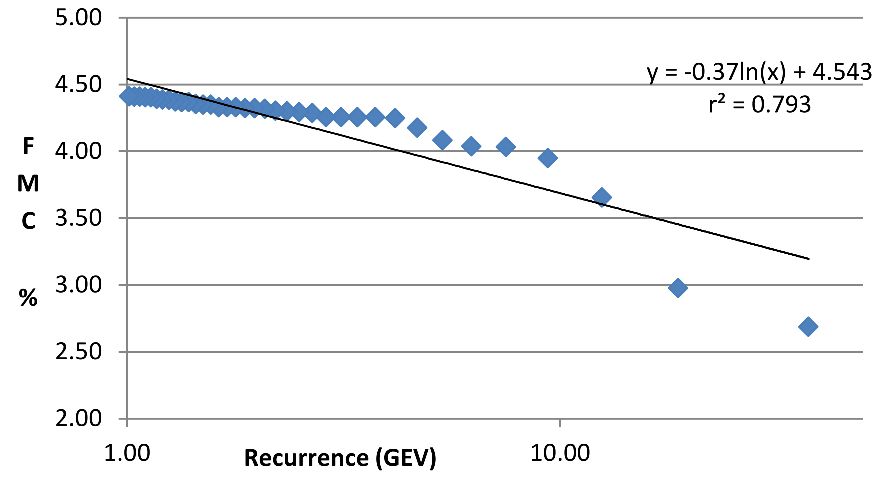
Fire Weather District: 15. Lower Central Western Plains (Dubbo)



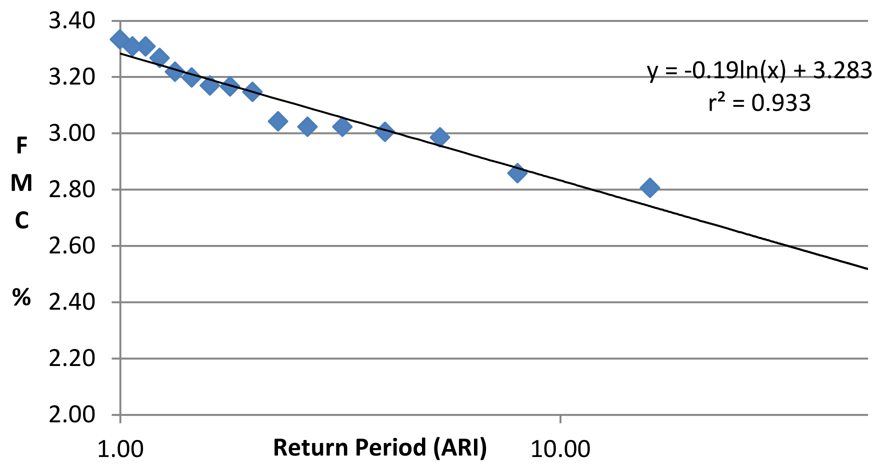
Fire Weather District: 16. Southern Slopes (Young).



Fire Weather District: 17. Eastern Riverina (Wagga Wagga).



Fire Weather District: 18. Southern Riverina (Deniliquin).



Shape parameters and Intercepts for FFDI& KBDI Western NSW weather stations (37 years of data).

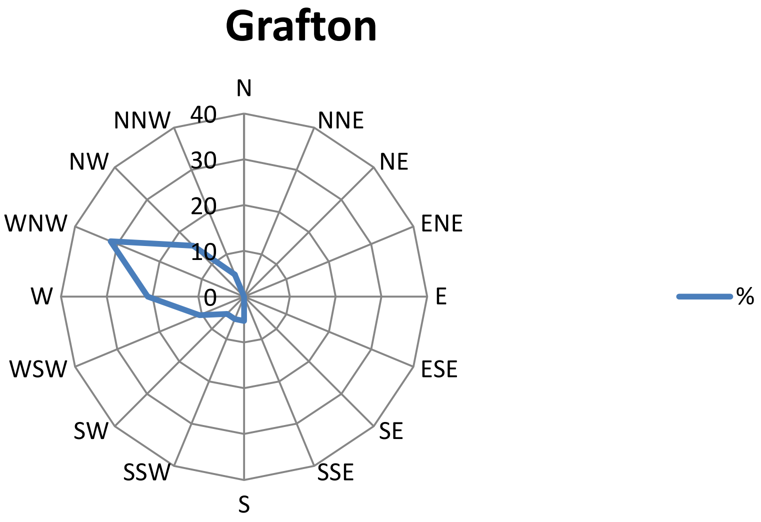
Weather Station	α	β	r^2	GEV_{50}
Mildura(FFDI)	13.965	78.432	0.9039	133.1
Cobar (FFDI)	11.952	67.482	0.9224	114.2
Hay (FFDI)	14.983	67.652	0.986	126.3
Mildura (KBDI)	1.9372	187.59	0.8329	195.2
Cobar (KBDI)	0.9316	189.13	0.9737	192.8
Hay (KBDI)	1.4727	182.07	0.9361	187.8

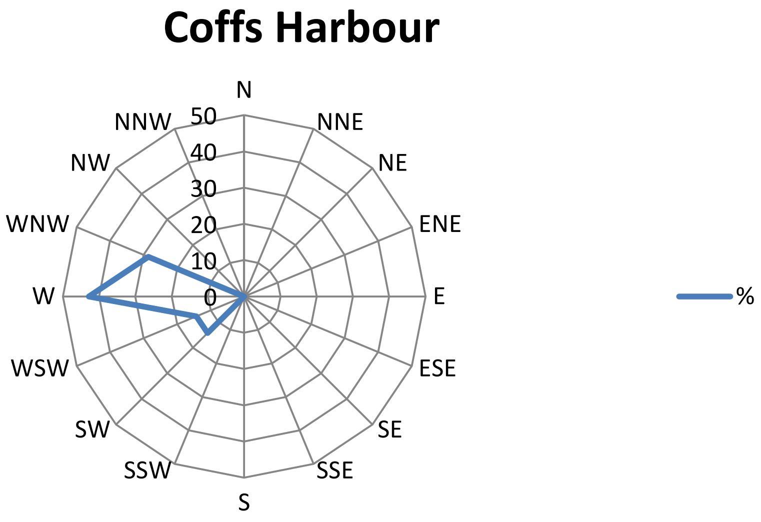
APPENDIX 7 - Shape Parameters and Intercept Values with Minimum Recorded FMC* for NSW Weather Stations

Fire Weather District	FMC (%) GEV_{50}	α	β	r^2	Minimum FMC Recorded*
1. Far North Coast	2.18	-0.451	3.9416	0.914	2.51
2. North Coast	1.53	-0.795	4.6449	0.945	2.26
3. Greater Hunter	1.92	-0.438	3.6348	0.984	2.17
4. Greater Sydney	2.32	-0.313	3.5399	0.979	2.44
5. Illaw/South Coast	2.44	-0.280	3.5323	0.966	2.68
6. Far South Coast	2.85	-0.342	4.1912	0.899	3.02
7. Monaro-Alpine	2.09	-0.128	2.5876	0.879	2.26
8. ACT	2.21	-0.262	3.2316	0.973	2.23
9. Southern Ranges	3.21	-0.128	3.7058	0.959	3.36
10. Central Ranges	2.30	-0.207	3.1135	0.949	2.60
11. New England	3.11	-0.224	3.9900	0.946	3.38
12. Northern Ranges	2.57	-0.142	3.1290	0.966	2.76
13. North-Western	1.90	-0.028	2.0103	0.946	1.93
14. Upper CW Plains	1.80	-0.317	3.0363	0.964	2.18
15. Lower CW Plains	1.95	-0.030	2.0702	0.929	1.98
16. Southern Slopes	2.15	-0.139	2.6897	0.849	2.40
17. Eastern Riverina	3.10	-0.372	4.5600	0.793	2.69
18. Southern Riverina	2.52	-0.196	3.2830	0.933	2.81
19. Northern Riverina	1.90	-0.028	2.0103	0.946	1.93
20. South-Western	2.09	-0.167	2.7423	0.964	2.08
21. Far Western	1.87	-0.106	2.2823	0.830	2.00

Note: * temperature and humidity recorded, calculation based on Cruz et al (2015).

APPENDIX 8 - Wind Directions (Wind Roses) for NSW Weather Stations FFDI≥50 (1972*-2009)

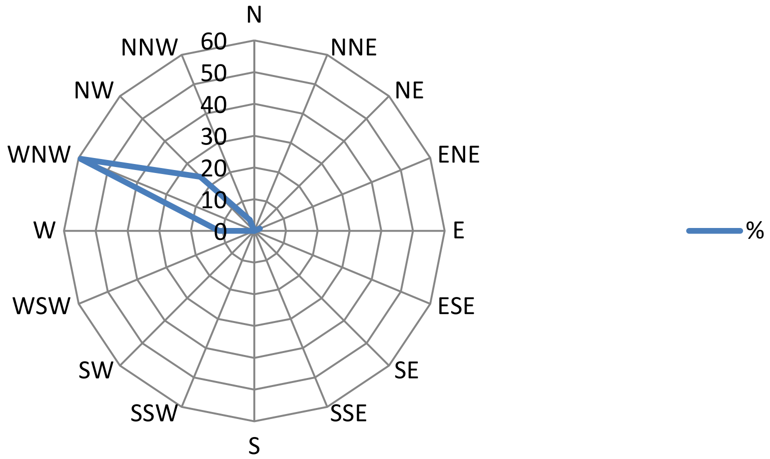




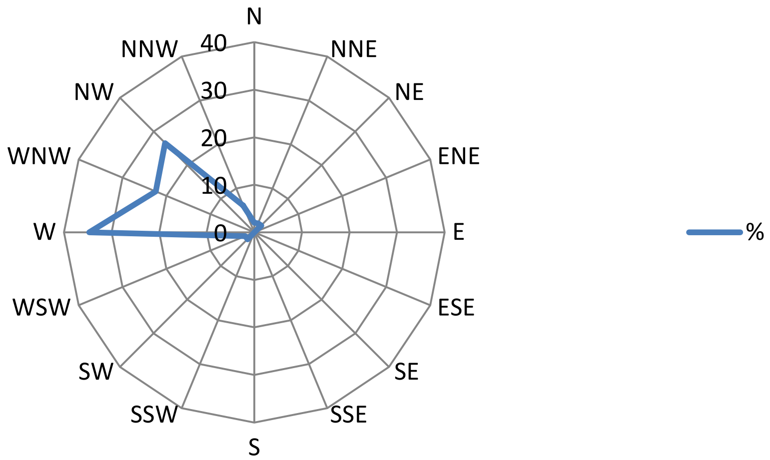
<u>NOTE</u>: Armidale has no FFDI>50 values, hence no wind roses are available. (See Appendix 10 below).

* Some weather stations only have data from 1994-2009.

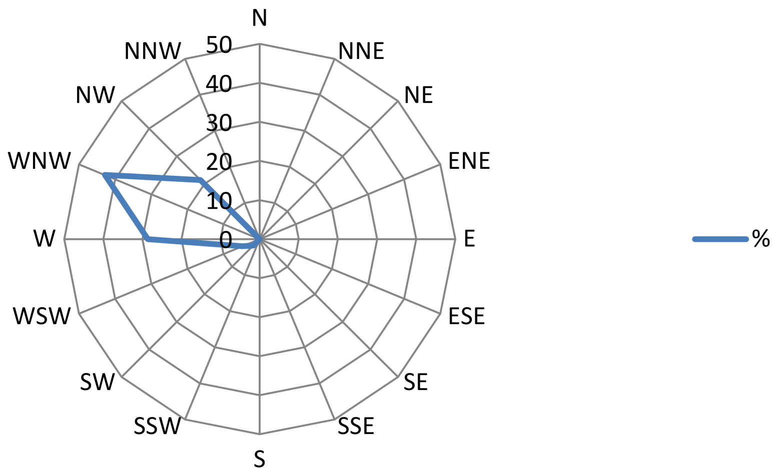
Williamtown

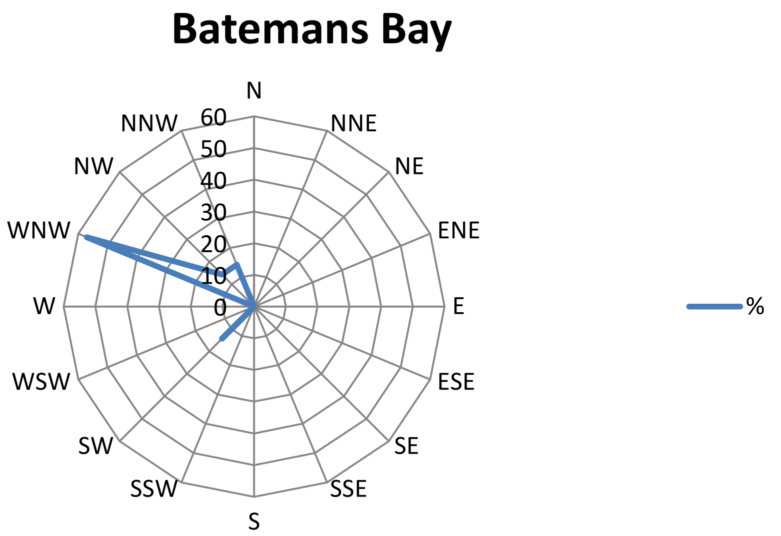


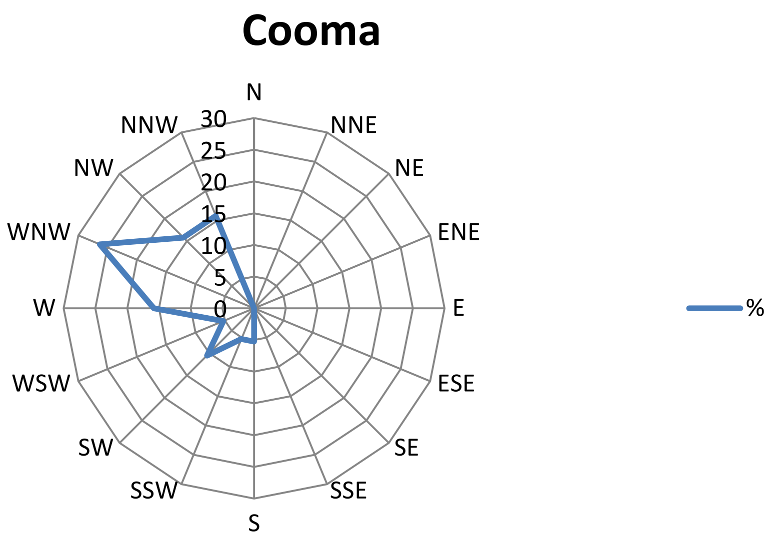
Sydney

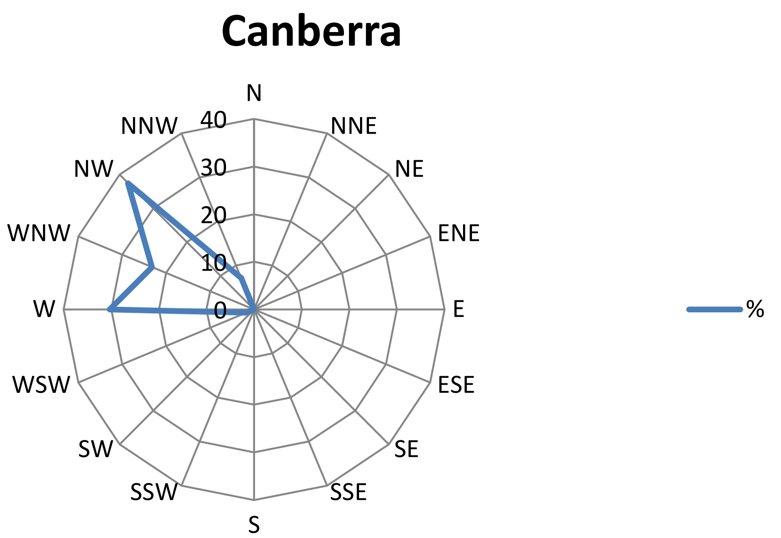


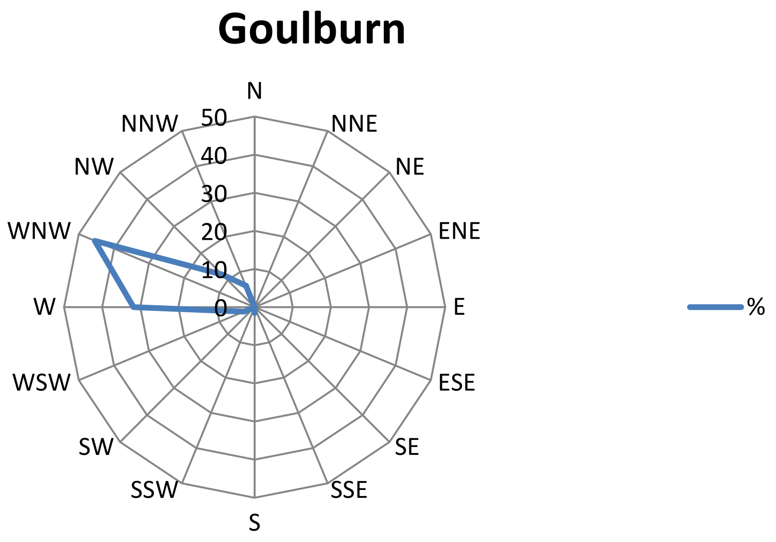
Nowra

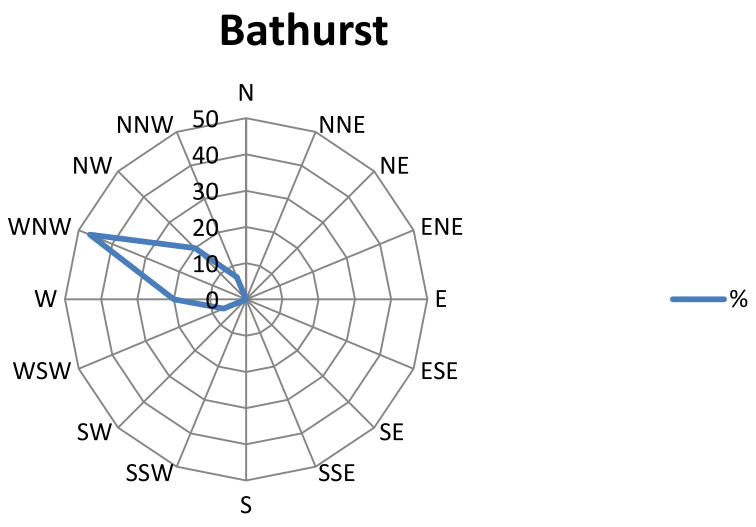


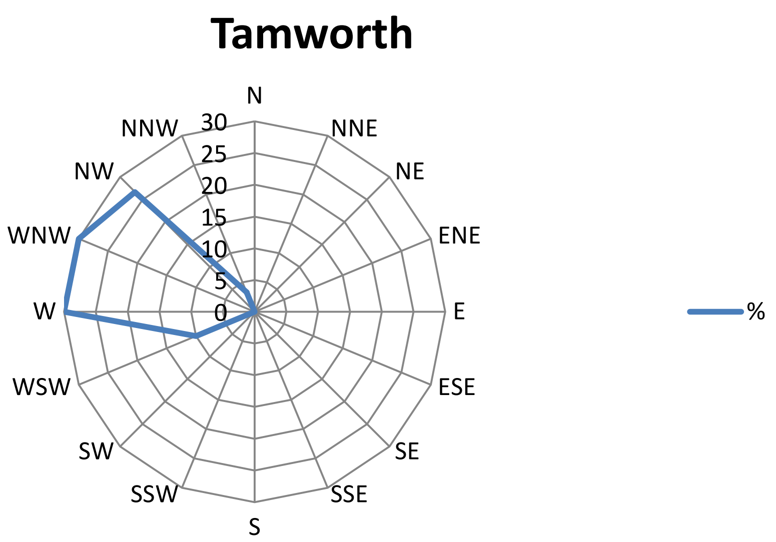

Batemans Bay
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
60
50
40
30
20
10
0
%

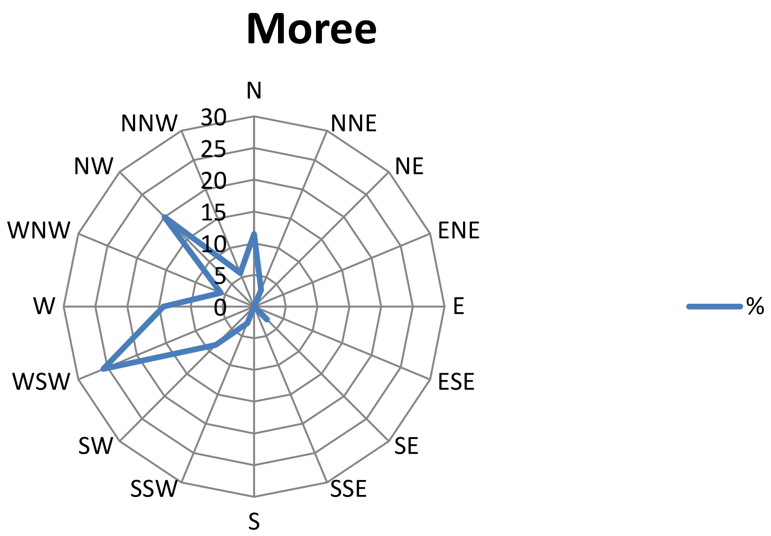

Cooma
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
30
25
20
15
10
5
0
%

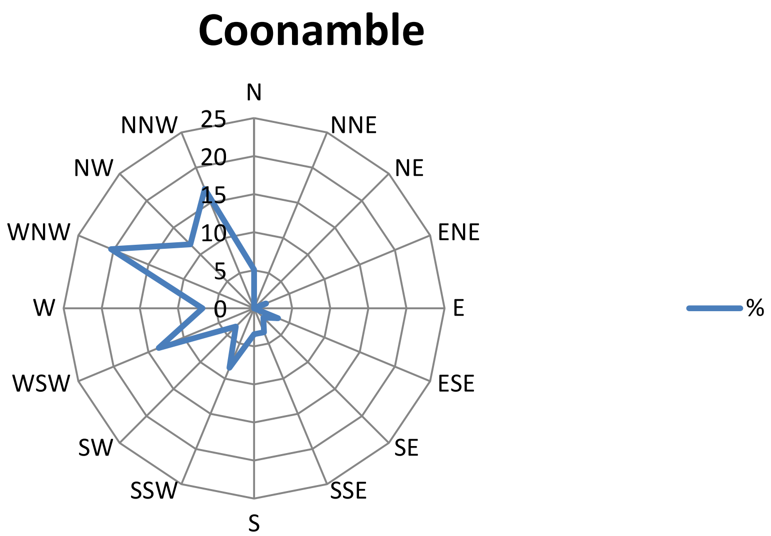

Canberra
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
40
30
20
10
0
%

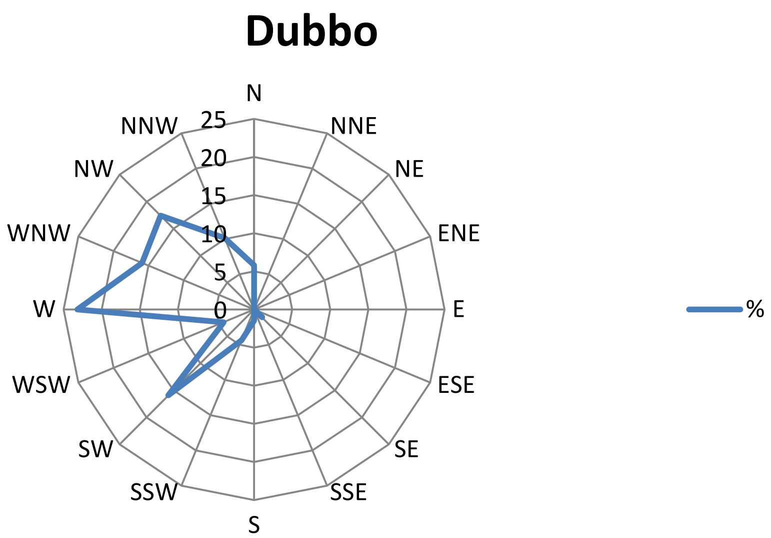

Goulburn
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
50
40
30
20
10
0
%

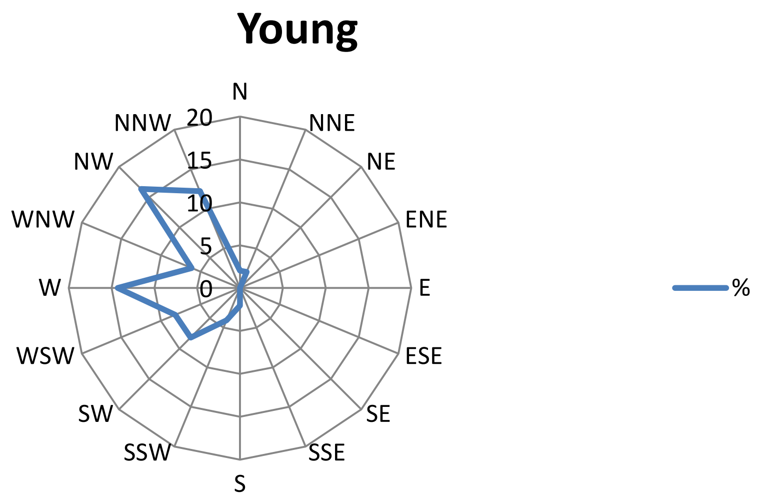

Bathurst
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
50
40
30
20
10
0
%

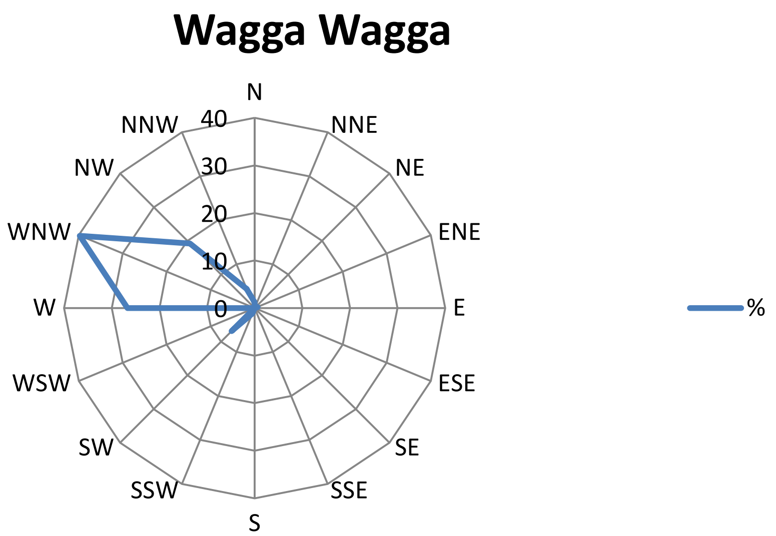

Tamworth
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
30
25
20
15
10
5
0
%

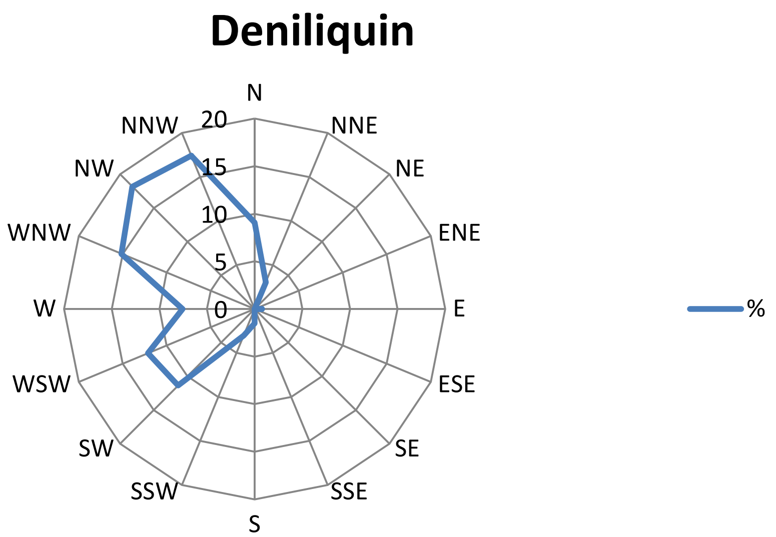

Moree
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
30
25
20
15
10
5
0
%


Coonamble
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
25
20
15
10
5
0
%

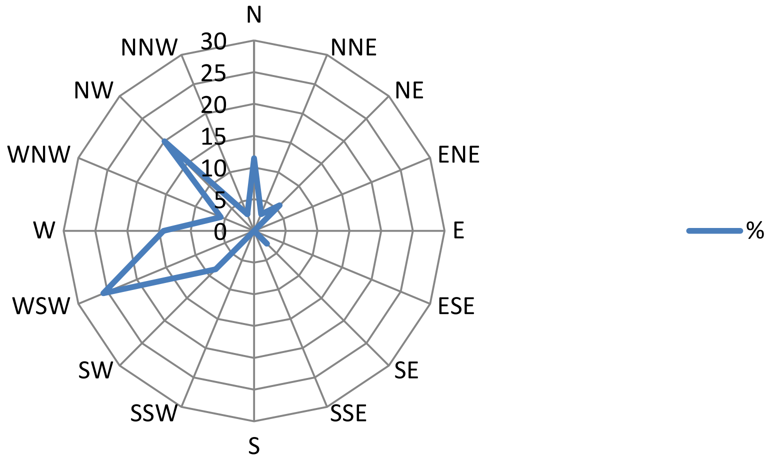

Dubbo
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
25
20
15
10
5
0
%


Young
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
20
15
10
5
0
%

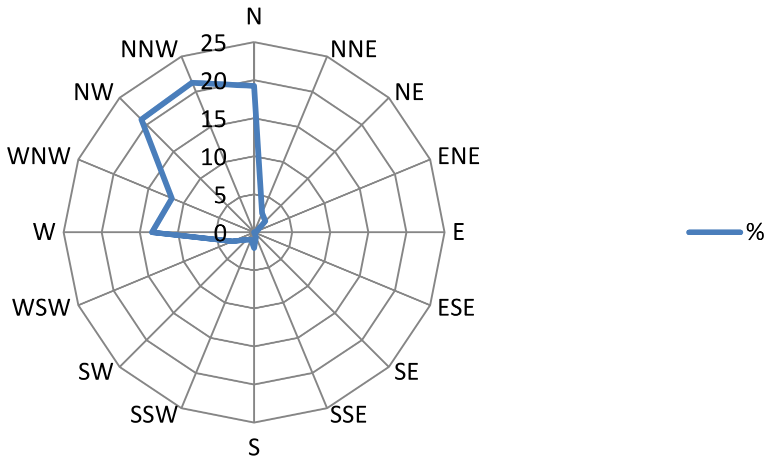

Wagga Wagga
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
40
30
20
10
0
%


Deniliquin
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
20
15
10
5
0
%

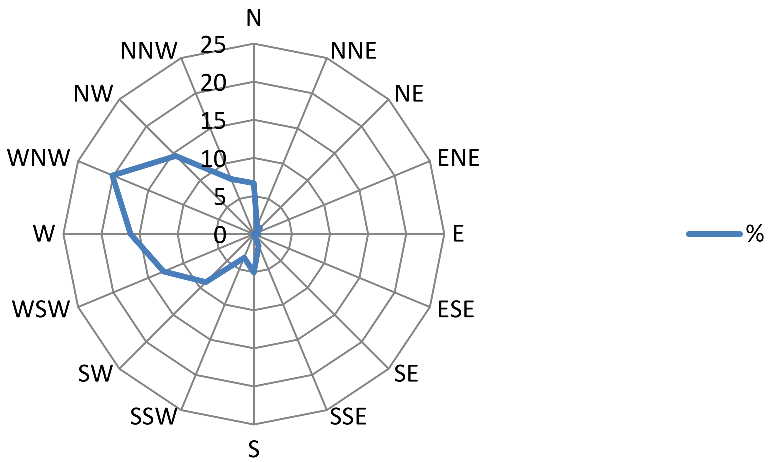
Hay



Mildura



Cobar



APPENDIX 9 - Wind Speed and Dominant wind directions @1500hrs (FFDI>50)

Fire Weather District	Weather Station	Highest wind speed	Mean of wind speeds	S.D. of wind speeds	Dominant wind direction	% of total	Direction Absent	Sample Size
1. Far North Coast	Grafton	38.9	30.4	6.04	SSW-NNW	95%	N-SSE	19
2. North Coast	Coffs Harbour	44.3	44.3	5.6	SW-WNW	100	NW-SSW	7
3. Greater Hunter	Williamtown	68	41.2	10.0	W-NNW	88	N-NE, E-WSW	56
4. Greater Sydney	Sydney Airport	65	39.1	8.7	W-NW	87	ENE-SSW	49
5. Illawarra/South Coast	Nowra	55.4	37.4	9.8	SW-NW	100	N-SSW	43
6. Far South Coast	Batemans Bay	83.2	53.4	20.9	WNW-NNW	86	N-SSW,WSW-W	7
7. Monaro-Alpine	Cooma	38.9	30.4	6.0	S-NNW	100	N-SSE	19
8. Australian Capital Territory	Canberra Airport	53.6	36.8	7.6	W-NNW	98	N-SW	56
9. Southern Ranges	Goulburn	57.2	39.1	8.6	W-NNW	97	ENE-SE	66
10. Central Ranges	Bathurst	55.4	39.0	9.6	S-NNW	100	N-SSE	15
11. New England	Armidale	N/A	N/A	N/A	N/A	0	N/A	0
12. Northern Ranges	Tamworth	50	35.8	8.14	WSW-NW	97	N-SW	30
13. North Western	Moree	68.4	37.7	14.4	SW-N	91	NE-ESE, SSE-S	34
14. Upper Central West Plains	Coonamble	68.4	33.0	12.35	SSW-N	86	NNE-NE, E	59
15. Lower Central West Plains	Dubbo	55.4	31.2	8.3	SW-N	89	NNE-ESE, SSE	69
16. Southern Slopes	Young	41	26	6.8	SW-NNW	98	NE-SSE	37
17. Eastern Riverina	Wagga Wagga	51.8	30.76	7.39	W-NW	86	NNE-NE, E-S	163
18. Southern Riverina	Deniliquin	68.4	29.3	9.6	SW-N	94	NE-ENE, ESE-SSE	132
19. Northern Riverina	Hay	68.4	37.7	14.2	SW-N	88	ENE-ESE, S	35

20. South Western	Mildura	55.4	28.6	9.8	W-N	87	ENE-SE	291
21. Far Western	Cobar	57	24.1	8.3	SW-N	87	ENE, ESE-S	179

APPENDIX 10 - 95% filtered data (@FFDI>12) for FFDI, Tmax, RH, DF and KBDI

Fire Weather District	Days of data		FFDI≥12				Tmax ^{0}C (FFDI≥12)					%RH (FFDI≥12)					DF (FFDI>12)				KBDI (mm) (FFDI≥12)			
	Total	≥12	95%	Av.	SD	max	95%	Av.	SD	min	max	5%	Av.	SD	min	max	95%	Av.	SD	min	95%	Av.	SD	max
1*FNC	5886	612	37	20	9.4	93	36	28	5.0	16.2	43.7	20	28.3	5.6	15	44	10	9.3	1.0	3.8	166	118	34.6	178
2 NC	13728	359	34	19	10.1	95	37	25	5.8	15.1	43.3	14	28.5	10.7	6	62	10	8.7	1.1	2.8	155	98	36.1	172
3 GH	13728	1490	45	21	11.6	99	39	29	6.3	13.0	44.4	14	29.2	9.6	5	55	10	8.2	1.3	1.7	160	81	44.1	180
4 GS	13728	1302	45	21	11.4	95	38	27	6.2	12.5	45.2	13	29.0	10.5	4	60	10	8.3	1.3	2.2	149	78	40.1	171
5 ISC	13728	1140	47	22	12.3	120	39	28	6.4	11.1	43.6	13	27.7	9.1	5	61	10	8.4	1.3	2.5	162	87	42.0	185
6*FSC	5887	294	42	21	10.5	74	34	24	5.0	13.8	44.8	15	26.4	8.7	7	57	10	8.0	1.4	3.5	140	64	40.0	162
7*MA	5887	1278	39	21	8.8	68	34	25	5.7	8.0	38.7	8	20.3	7.8	1	53	9.6	7.7	1.3	2.7	109	54	31.4	121
8 ACT	13728	2315	42	21	10.1	99	36	29	4.9	13.4	40.5	12	23.2	7.0	4	50	9.9	8.1	1.2	3.1	137	69	36.8	158
9* SR	5887	1298	50	24	12.0	90	35	26	5.6	8.8	40.4	11	23.0	8.1	2	50	9.9	8.2	1.3	2.9	125	67	34.2	144
10*CR	5887	1110	37	21	8.6	72	35	27	5.4	7.8	40.7	11	22.9	7.4	3	47	9.9	8.1	1.3	3.3	121	65	31.6	134
11*NE	5887	223	24	16	4.7	46	34	27	4.9	10.5	36.1	13	22.5	6.2	9	37	9.0	7.4	1.1	4.1	75	42	20.4	96
12*NR	5885	2035	40	21	9.2	105	38	29	5.4	11.8	42.0	13	25.0	7.5	5	53	10	8.9	1.1	3.3	156	96	38.0	173
13 NW	13728	3648	36	20	8.6	125	41	32	5.4	12.4	46.3	12	22.8	6.7	3	62	10	9.3	0.9	4.6	166	115	37.3	186
14*UCW	5887	2370	42	22	10.4	121	39	31	5.8	14.0	45.1	12	24.2	7.4	1	56	10	9.1	1.0	3.4	169	108	38.8	185
15 LCW	13728	3732	40	21	9.6	99	39	31	5.2	12.4	44.5	12	24.5	7.3	5	51	10	8.8	1.1	2.3	163	98	41.6	192
16*SS	5887	1861	41	22	9.5	71	38	29	5.2	13.5	42.5	11	22.5	7.4	3	47	10	8.9	1.2	3.5	163	97	42.2	184
17ERi	13728	3877	47	23	12.0	138	39	31	5.1	13.1	45.2	10	21.9	7.4	2	54	10	8.8	1.2	3.4	163	99	42.5	178
18*SRi	5886	2303	51	25	13.1	121	39	29	6.0	11.5	46.6	9	22.6	8.2	2	49	10	9.3	1.0	4.1	161	110	35.3	180
19Nri	13728	3648	36	20	8.6	125	41	32	5.4	12.4	46.3	12	22.8	6.7	3	62	10	9.3	1.0	4.6	166	115	37.3	186
20 SW	13728	6236	49	24	12.3	132	39	29	5.9	13.8	46.9	10	22.9	7.8	0	77	10	9.5	0.8	3.8	170	125	36.1	192
21 FW	13728	6025	44	24	10.8	117	40	31	5.7	12.4	47	9	20.2	7.3	0	49	10	9.2	1.0	3.0	178	117	41.5	192

Note: Data from 1972-2015 (*some data from 1994-2015)

APPENDIX 11- Shape Curve and Intercept Parameters with Recurrence Values for GEV_{50} KBDI (1972-2015)

Fire Weather District (No) Weather Station	***α***	***β***	r^2	**GEV(50) KBDI**
1. Grafton*	2.1575	172.81	0.9131	181.3
2. Coffs Harbour	2.8975	165.47	0.8401	176.8
3. Williamtown	1.8642	174.4	0.9127	181.7
4. Sydney	2.4415	164.41	0.9691	174.0
5. Nowra	4.8885	173.25	0.8198	192.4
6. Batemans Bay*	2.6137	155.86	0.9575	166.1
7. Cooma*	1.8561	116.49	0.8959	123.8
8. Canberra	1.8611	152.38	0.9282	159.7
9. Goulburn*	1.8539	139.45	0.9065	146.7
10. Bathurst*	1.9261	130.88	0.9519	138.4
11. Armidale*	3.9261	93.56	0.9641	108.9
12. Tamworth*	0.6164	176.73	0.6449	179.1
13. Moree	1.8971	180.99	0.8957	188.4
14. Coonamble*	1.2645	187.79	0.8792	192.7
15. Dubbo	3.3127	184.6	0.7204	197.6
16. Deniliquin*	0.8842	182.17	0.7421	185.6
17. Wagga Wagga	1.6782	173.35	0.853	179.9
18. Young*	2.5035	174.73	0.7876	184.5
* Data from 1994-2009				

APPENDIX 12 - Correlation Coefficients for DEFFM for Rates of Spread, Flame Heightsand FMCandFFDM5

Fire Weather District	GEV_{50} Correlation Coefficients (r^2)			
	DEFFM ROS	*DEFFM FH*	*DEFFM FMC*	*FFDM5*
1.FNC	0.917	0.908	0.937	0.971
2.NC	0.697	0.618	0.967	0.972
3.GHu	0.988	0.987	0.928	0.977
4.GSy	0.969	0.978	0.981	0.985
5.ISC	0.957	0.940	0.967	0.946
6.FSC	0.967	0.964	0.986	0.962
7.MA	0.904	0.909	0.788	0.916
8.ACT	0.985	0.987	0.920	0.968
9.SR	0.877	0.866	0.867	0.957
10.CR	0.952	0.944	0.922	0.970
11.NE	0.939	0.942	0.948	0.957
12.NS	0.937	0.920	0.966	0.922
13.NW	0.967	0.972	0.850	0.913
14.UCW	0.922	0.906	0.964	0.968
15.LCW	0.925	0.937	0.898	0.986
16.SSl	0.956	0.954	0.869	0.955
17.ERi	0.982	0.979	0.910	0.940
18.SRi	0.864	0.869	0.984	0.940

APPENDIX 13 - Flame Height and Rates of Spread (DEFFM) Shape Parameters and Intercepts for 9 Vegetation Classes in 18 NSW Fire Weather Districts.

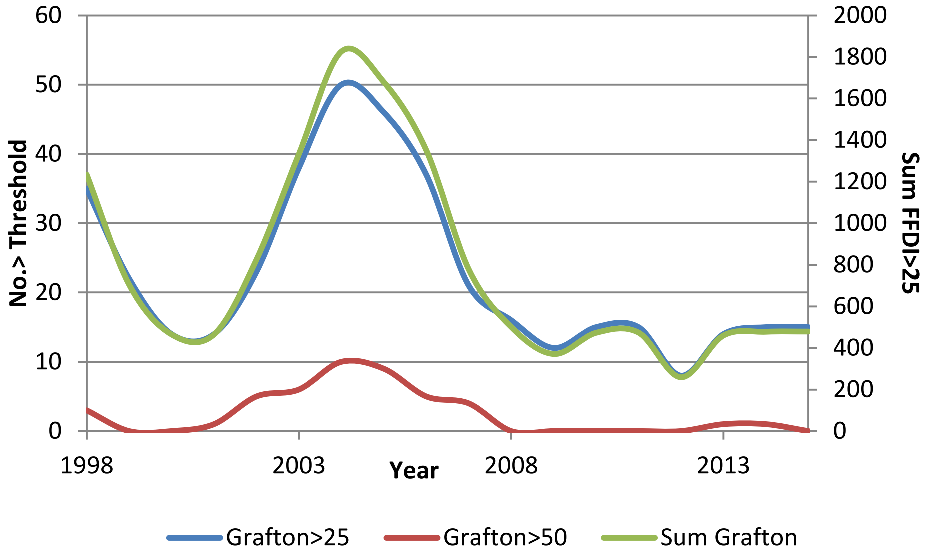
Flame height (DEFFM)																			
Fire Weather District	Forest Vegetation Classes																		
	NC-WSF		NH-WSF		NC-DSF		Syd-DSF		SE-DSF		ST-DSF		HM-DSF		Cu-DSF		CVGW		r^2
	α	β	α	β	α	β	α	β	α	β	α	β	α	β	α	β	α	β	
1.FNC	9.80	37.36	10.156	38.718	8.958	34.136	10.707	40.867	7.202	27.474	2.355	9.041	7.179	27.432	2.961	11.405	4.062	15.592	0.917
2.NC	11.37	19.68	11.916	20.167	10.393	17.973	12.434	21.530	8.361	14.472	2.745	4.772	8.343	14.458	3.457	6.028	4.734	8.231	0.697
3.GHu	9.21	40.41	9.550	41.880	8.424	36.928	10.070	44.192	6.773	29.713	2.216	9.762	6.752	29.655	2.787	12.305	3.822	16.837	0.988
4.GSy	9.65	39.62	10.004	41.056	8.847	36.157	10.585	43.280	7.118	29.098	2.337	9.569	7.102	29.048	2.945	12.068	3.147	20.261	0.969
5.ISC	8.94	40.45	9.235	41.969	8.146	37.005	9.736	44.293	6.548	29.779	2.141	9.792	6.527	29.727	2.691	12.348	3.693	16.888	0.957
6.FSC	4.72	45.42	4.898	47.071	4.332	41.488	5.165	49.666	3.474	33.395	1.137	10.969	3.463	33.327	1.429	13.823	1.961	18.918	0.967
7.MA	9.13	59.31	9.470	61.462	8.354	54.185	9.982	64.886	6.715	43.619	2.194	14.367	6.691	43.562	2.756	18.135	3.784	24.778	0.904
8.ACT	7.57	48.61	7.842	50.376	6.915	44.419	8.272	53.161	5.563	35.742	1.825	11.748	5.550	35.676	2.298	14.810	3.147	20.261	0.985
9.SR	7.01	55.40	7.277	57.425	6.419	50.643	7.672	60.572	5.160	40.733	1.687	13.357	5.146	40.632	2.121	18.815	2.910	23.036	0.877
10.CR	8.58	49.68	8.900	51.486	7.851	45.398	9.380	54.331	6.310	36.529	2.061	12.005	6.288	36.460	2.588	15.133	3.555	20.704	0.952
11.NE	5.68	31.27	5.944	32.318	5.245	28.483	5.805	61.280	4.212	22.944	1.369	7.582	4.191	22.934	1.714	9.589	2.361	13.076	0.939
12.NS	5.32	56.03	5.516	58.065	4.870	51.197	6.259	34.139	3.908	41.200	1.266	13.547	3.885	41.128	1.582	17.082	2.183	23.364	0.937
13.NW	11.41	79.96	11.834	82.859	10.445	73.053	12.458	87.462	8.385	58.799	2.722	19.352	8.341	58.711	3.405	24.416	4.694	33.376	0.967
14.UCW	13.63	51.98	14.135	53.868	12.470	47.494	14.896	56.857	10.021	38.224	3.270	12.576	9.983	38.164	4.105	15.864	5.640	21.690	0.922
15.LCW	15.55	55.31	16.127	57.290	14.236	50.479	16.971	60.560	11.424	40.689	3.700	13.493	11.358	40.711	4.624	17.100	6.382	23.270	0.925
16.SSl	5.65	48.31	5.852	50.054	5.162	44.122	6.172	52.855	4.151	35.527	1.356	11.723	9.983	38.164	1.704	14.812	2.338	20.218	0.956
17.ERi	4.17	35.81	4.324	37.110	3.814	32.271	4.558	39.163	3.066	26.33	1.003	8.656	3.056	26.283	1.261	10.913	1.730	14.928	0.982
18.SRi	7.81	50.10	8.095	51.928	7.137	45.792	8.546	54.784	5.745	36.838	1.892	12.092	5.738	36.756	2.389	15.521	3.264	20.854	0.864

	Rates of Spread (DEFFM)																		
Fire Weather District	**Forest Vegetation Classes**																		
	NC-WSF		NH-WSF		NC-DSF		SyC-DSF		SE-DSF		ST-DSF		HM-DSF		Cu-DSF		CVGW		r^2
	α	β	α	β	α	β	α	β	α	β	α	β	α	β	α	β	α	β	
1.FNC	3348	1365	3518	1435	3787	1545	3012	1227	3203	1305	1775	718.5	2631	1070	1402	565.0	1778	719.6	0.908
2.NC	1179	1537	1239	1615	1333	1739	1061	1382	1128	1470	628.2	812.3	927.8	1206	497.4	640.3	629.1	813.5	0.618
3.GHu	3719	1323	3908	1391	4207	1498	3344	1189	3557	1265	1968	696.7	2920	1037	1552	547.9	1970	697.7	0.987
4.GSy	3619	1377	3802	1446	4093	1557	3254	1238	3461	1317	1916	728.1	2842	1081	1512	574.1	1919	729.1	0.978
5.ISC	3717	1294	3906	1361	4204	1466	3343	1163	3555	1238	1969	681.2	2920	1015	1554	535.5	1972	682.2	0.940
6.FSC	4419	668.5	4643	702.6	4999	756.7	3973	600.8	4226	639.2	2336	352.1	3468	524.1	1842	277.0	2339	352.6	0.964
7.MA	6356	1474	6677	1550	7187	1669	5718	1325	6080	1410	3374	776.0	4995	1156	2666	610.2	3378	777.2	0.909
8.ACT	4837	1129	5082	1186	5471	1277	4262	1079	4349	1015	2560	596.0	3738	885.6	2019	469.5	2564	596.9	0.987
9.SR	5827	1078	6123	1133	6594	1220	5237	968.2	5572	1031	3074	566.1	4571	844.3	2421	444.6	3079	566.9	0.866
10.CR	4999	1287	5253	1352	5655	1457	4495	1156	4781	1230	2645	676.3	3925	1008	2086	531.4	2649	677.3	0.944
11.NE	2617	722.8	2749	759.8	2958	818.6	2356	649.1	2504	690.9	1936	378.6	2060	565.7	1106	296.9	1398	379.1	0.942
12.NS	5856	845.1	6153	888.6	6623	957.7	5266	758.5	5601	807.7	3100	440.9	4598	660.6	2446	344.9	3105	441.5	0.920
13.NW	9639	2046	10127	2152	10901	2319	8670	1837	9220	1956	5112	1068	7573	1600	4037	836.1	5119	1070	0.972
14.UCW	5293	2158	5560	2268	5985	2444	4760	1939	5062	2063	2806	1133	4158	1690	2215	889.4	2810	1135	0.906
15.LCW	5750	2531	6037	2661	6492	2868	5179	2272	5503	2419	3084	1321	4533	1979	2451	1034	3088	1323	0.937
16.SSl	4822	814.9	5065	856.6	5450	922.7	4339	732.0	4613	779.1	2568	427.9	3793	638.3	2033	336.0	2571	428.5	0.954
17.ERi	3175	547.0	3336	574.9	3591	619.2	2855	491.5	4613	779.1	1680	288.0	2568	427.9	1326	226.5	1683	288.4	0.979
18.SRi	5064	1156	5321	1214	5730	1307	5552	1040	4843	1106	2675	612.8	3974	908.1	2108	483.9	2679	613.7	0.869

APPENDIX 14 - 4 year moving Frequency of Exceedance (FFDI≥25 and FFDI≥50) and Cumulative FFDI≥25*

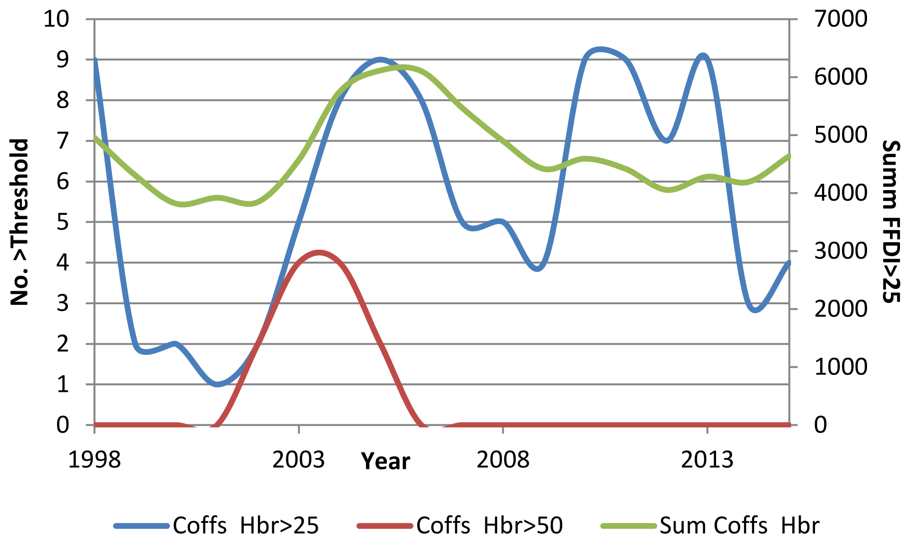
Grafton

Years	No. FFDI>25	No. FFDI>50	∑FFDI>25
1994-98	35	3	1234
1995-99	22	0	705
1996-00	14	0	465
1997-01	14	1	465
1998-02	23	5	825
1999-03	38	6	1333
2000-04	50	10	1826
2001-05	46	9	1679
2002-06	37	5	1351
2003-07	21	4	778
2004-08	16	0	501
2005-09	12	0	371
2006-10	15	0	473
2007-11	15	0	474
2008-12	8	0	259
2009-13	14	1	460
2010-14	15	1	478
2011-15	15	0	479
Av/yr	5.7	0.6	196.6



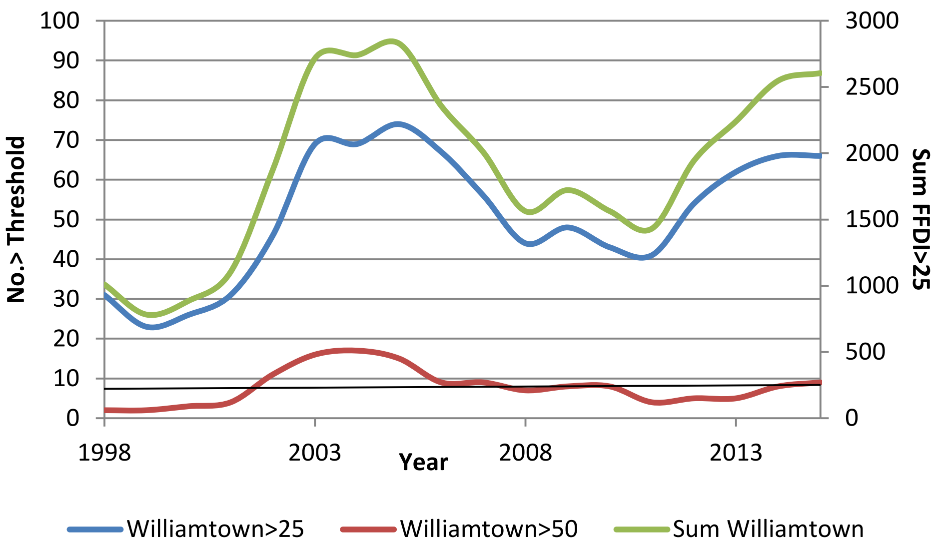
Coffs Hbr

Years	No. FFDI>25	No. FFDI>50	∑FFDI>25
1994-98	9	0	4956
1995-99	2	0	4305
1996-00	2	0	3817
1997-01	1	0	3919
1998-02	2	2	3846
1999-03	5	4	4569
2000-04	8	4	5745
2001-05	9	2	6113
2002-06	8	0	6101
2003-07	5	0	5467
2004-08	5	0	4895
2005-09	4	0	4415
2006-10	9	0	4592
2007-11	9	0	4416
2008-12	7	0	4054
2009-13	9	0	4282
2010-14	3	0	4191
2011-15	4	0	4636
Av/yr	1.4	0.2	1171.1



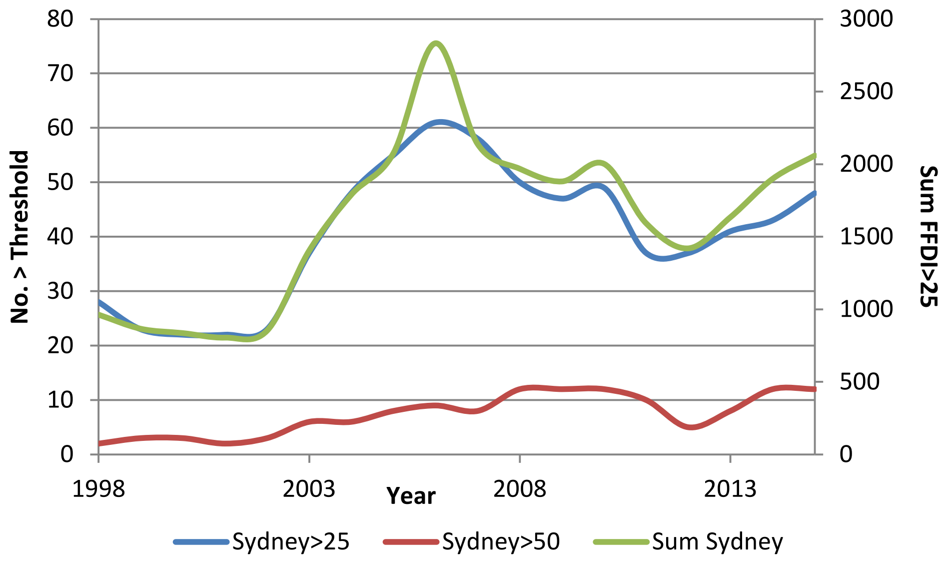
Williamtown

Years	No. FFDI>25	No. FFDI>50	∑FFDI>25
1994-98	31	2	1010
1995-99	23	2	782
1996-00	26	3	886
1997-01	31	4	1105
1998-02	46	11	1876
1999-03	69	16	2716
2000-04	69	17	2741
2001-05	74	15	2828
2002-06	67	9	2357
2003-07	56	9	2007
2004-08	44	7	1562
2005-09	48	8	1722
2006-10	43	8	1563
2007-11	41	4	1431
2008-12	54	5	1944
2009-13	62	5	2242
2010-14	66	8	2548
2011-15	66	9	2605
Av/yr	12.7	2.0	471.2



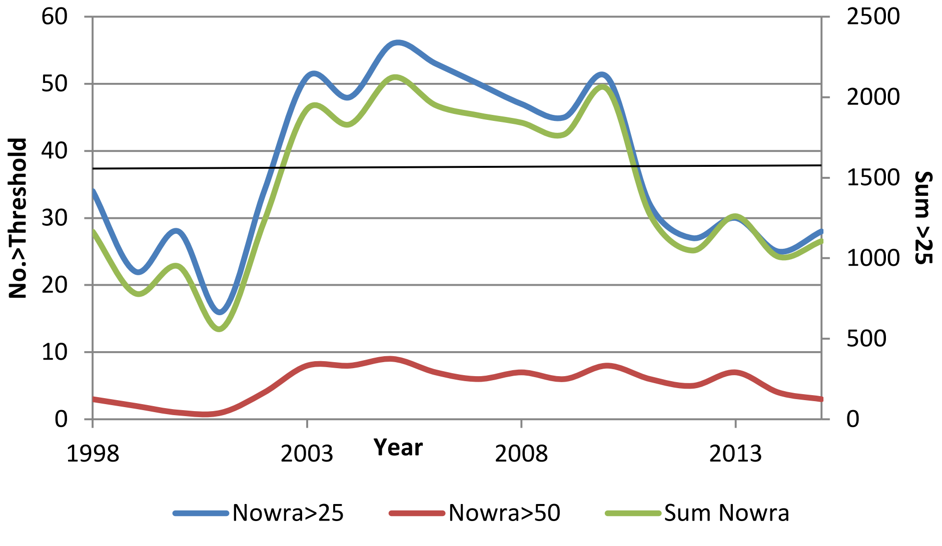
Sydney

Years	No. FFDI>25	No. FFDI>50	∑FFDI>25
1994-98	28	2	963
1995-99	23	3	866
1996-00	22	3	836
1997-01	22	2	805
1998-02	23	3	853
1999-03	37	6	1404
2000-04	48	6	1790
2001-05	55	8	2076
2002-06	61	9	2833
2003-07	58	8	2138
2004-08	50	12	1968
2005-09	47	12	1881
2006-10	49	12	2002
2007-11	37	10	1592
2008-12	37	5	1420
2009-13	41	8	1635
2010-14	43	12	1899
2011-15	48	12	2059
Av/yr	10.1	1.8	403.1



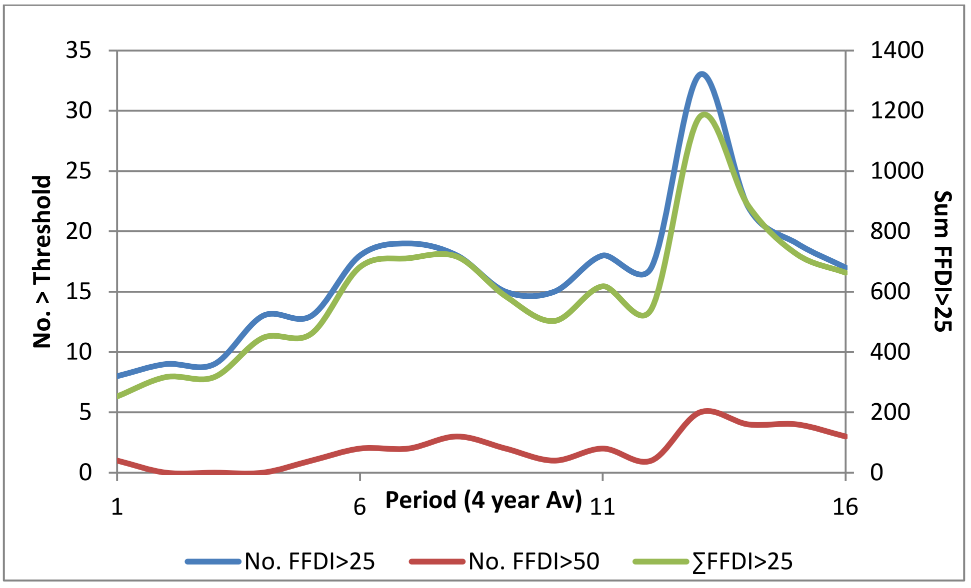
Nowra

Years	No. FFDI>25	No. FFDI>50	∑FFDI>25
1994-98	34	3	1165
1995-99	22	2	781
1996-00	28	1	950
1997-01	16	1	563
1998-02	34	4	1230
1999-03	51	8	1925
2000-04	48	8	1832
2001-05	56	9	2123
2002-06	53	7	1950
2003-07	50	6	1887
2004-08	47	7	1842
2005-09	45	6	1769
2006-10	51	8	2051
2007-11	32	6	1272
2008-12	27	5	1048
2009-13	30	7	1261
2010-14	25	4	1009
2011-15	28	3	1106
Av/yr	9.4	1.3	357.8



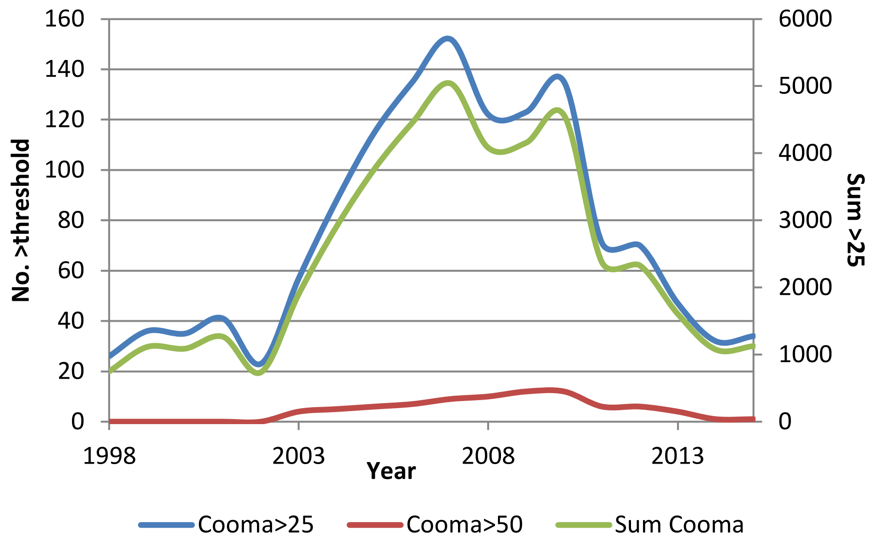
Batemans Bay

Years	No. FFDI>25	No. FFDI>50	∑FFDI>25
1994-98	8	1	253
1995-99	9	0	317
1996-00	9	0	317
1997-01	13	0	447
1998-02	13	1	461
1999-03	18	2	682
2000-04	19	2	711
2001-05	18	3	716
2002-06	15	2	585
2003-07	15	1	503
2004-08	18	2	618
2005-09	17	1	542
2006-10	33	5	1180
2007-11	22	4	884
2008-12	19	4	724
2009-13	17	3	663
2010-14	NA	NA	NA
2011-15	NA	NA	NA
Av/yr	3.9	0.5	150



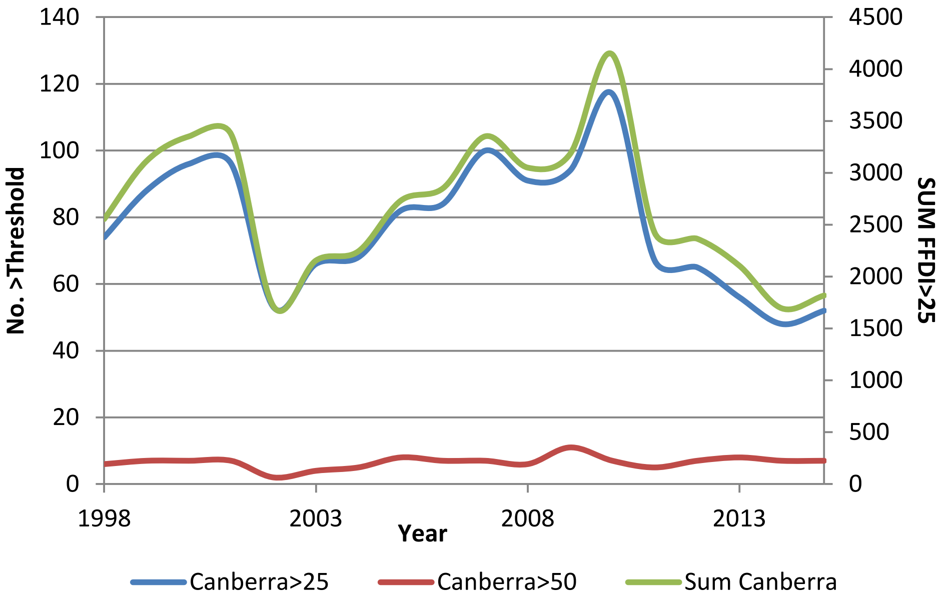
Cooma

Years	No. FFDI>25	No. FFDI>50	∑FFDI>25
1994-98	26	0	751
1995-99	36	0	1114
1996-00	35	0	1088
1997-01	41	0	1265
1998-02	23	0	736
1999-03	57	4	1904
2000-04	88	5	2911
2001-05	115	6	3768
2002-06	135	7	4457
2003-07	152	9	5040
2004-08	122	10	4080
2005-09	123	12	4156
2006-10	135	12	4564
2007-11	71	6	2374
2008-12	70	6	2327
2009-13	47	4	1605
2010-14	32	1	1075
2011-15	34	1	1126
Av/yr	18.6	1.2	615.8



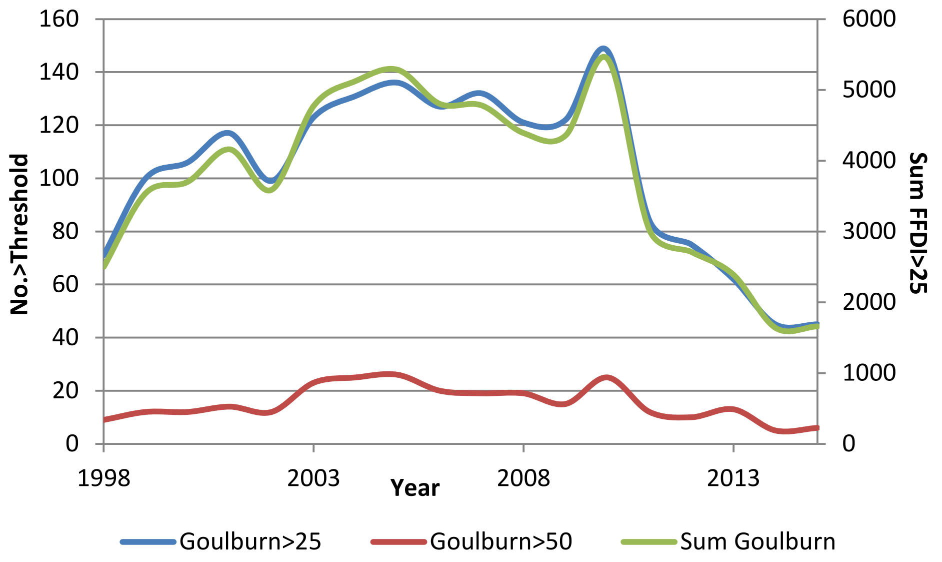
Canberra

Years	No. FFDI>25	No. FFDI>50	∑FFDI>25
1994-98	74	6	2554
1995-99	88	7	3113
1996-00	96	7	3351
1997-01	96	7	3369
1998-02	53	2	1711
1999-03	66	4	2155
2000-04	68	5	2243
2001-05	82	8	2731
2002-06	84	7	2851
2003-07	100	7	3352
2004-08	91	6	3050
2005-09	94	11	3181
2006-10	117	7	4140
2007-11	67	5	2421
2008-12	65	7	2365
2009-13	56	8	2104
2010-14	48	7	1694
2011-15	52	7	1818
Av/yr	19.4	1.6	669.5



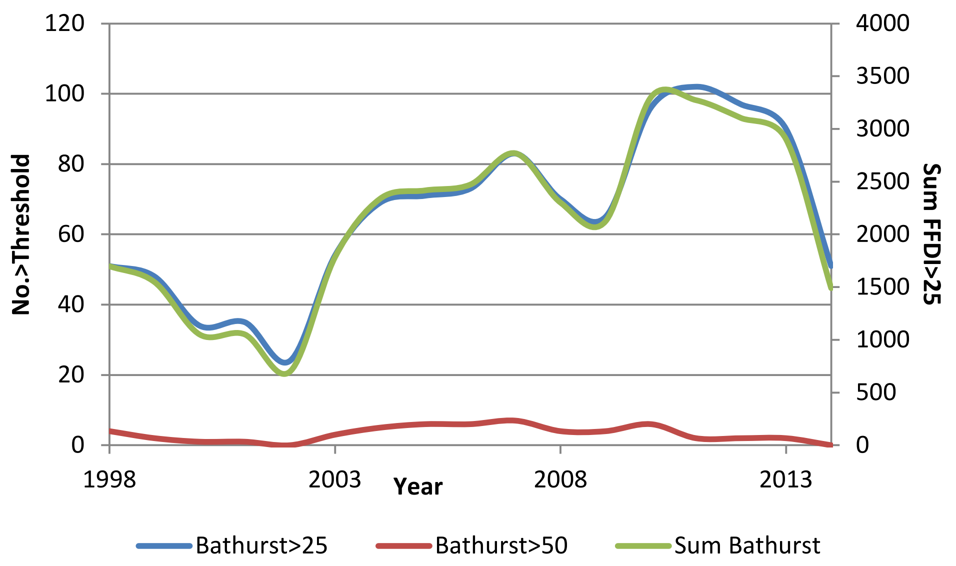
Goulburn

Years	No. FFDI>25	No. FFDI>50	∑FFDI>25
1994-98	71	9	2499
1995-99	100	12	3540
1996-00	106	12	3700
1997-01	117	14	4159
1998-02	99	12	3588
1999-03	123	23	4771
2000-04	131	25	5124
2001-05	136	26	5283
2002-06	127	20	4802
2003-07	132	19	4780
2004-08	121	19	4389
2005-09	122	15	4354
2006-10	148	25	5437
2007-11	84	12	3016
2008-12	75	10	2709
2009-13	62	13	2388
2010-14	45	5	1638
2011-15	45	6	1659
Av/yr	25.6	3.8	942.2



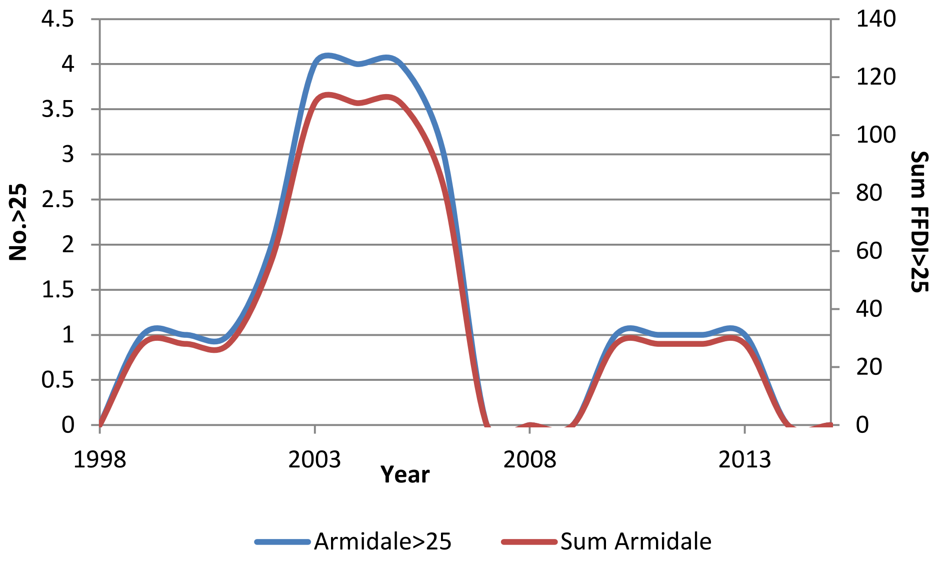
Bathurst

Years	No. FFDI>25	No. FFDI>50	∑FFDI>25
1994-98	51	4	1698
1995-99	48	2	1547
1996-00	34	1	1050
1997-01	35	1	1051
1998-02	24	0	698
1999-03	54	3	1784
2000-04	69	5	2338
2001-05	71	6	2417
2002-06	73	6	2472
2003-07	83	7	2769
2004-08	70	4	2301
2005-09	65	4	2125
2006-10	96	6	3298
2007-11	102	2	3273
2008-12	97	2	3104
2009-13	90	2	2902
2010-14	51	0	1490
2011-15	0	0	0
Av/yr	15.5	0.8	504.4



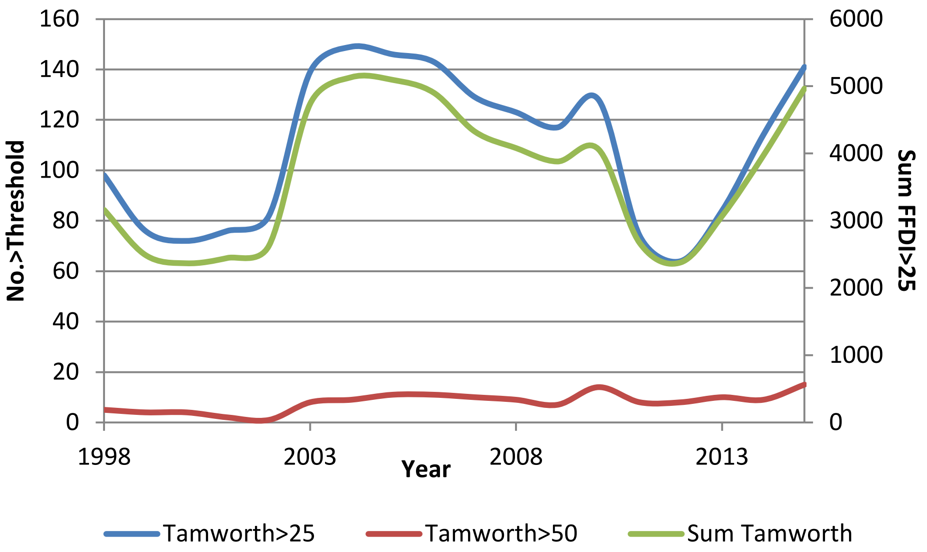
Armidale

Years	No. FFDI>25	Armidale	Armidale
1994-98	0	0	0
1995-99	1	0	28
1996-00	1	0	28
1997-01	1	0	28
1998-02	2	0	57
1999-03	4	0	111
2000-04	4	0	111
2001-05	4	0	111
2002-06	3	0	82
2003-07	0	0	0
2004-08	0	0	0
2005-09	0	0	0
2006-10	1	0	28
2007-11	1	0	28
2008-12	1	0	28
2009-13	1	0	28
2010-14	0	0	0
2011-15	0	0	0
Av/yr	0.3	0	9.3



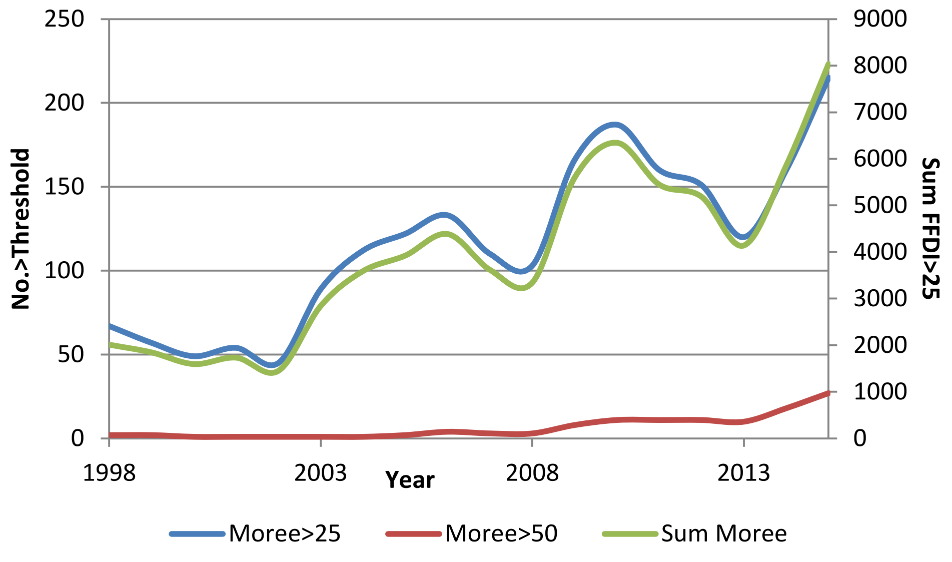
Tamworth

Years	No. FFDI>25	No. FFDI>50	∑FFDI>25
1994-98	98	5	3160
1995-99	76	4	2491
1996-00	72	4	2367
1997-01	76	2	2447
1998-02	82	1	2628
1999-03	139	8	4739
2000-04	149	9	5134
2001-05	146	11	5095
2002-06	143	11	4904
2003-07	129	10	4325
2004-08	123	9	4080
2005-09	117	7	3881
2006-10	128	14	4063
2007-11	74	8	2669
2008-12	64	8	2381
2009-13	84	10	3070
2010-14	114	9	3968
2011-15	141	15	4966
Av/yr	27.2	2.0	921.8



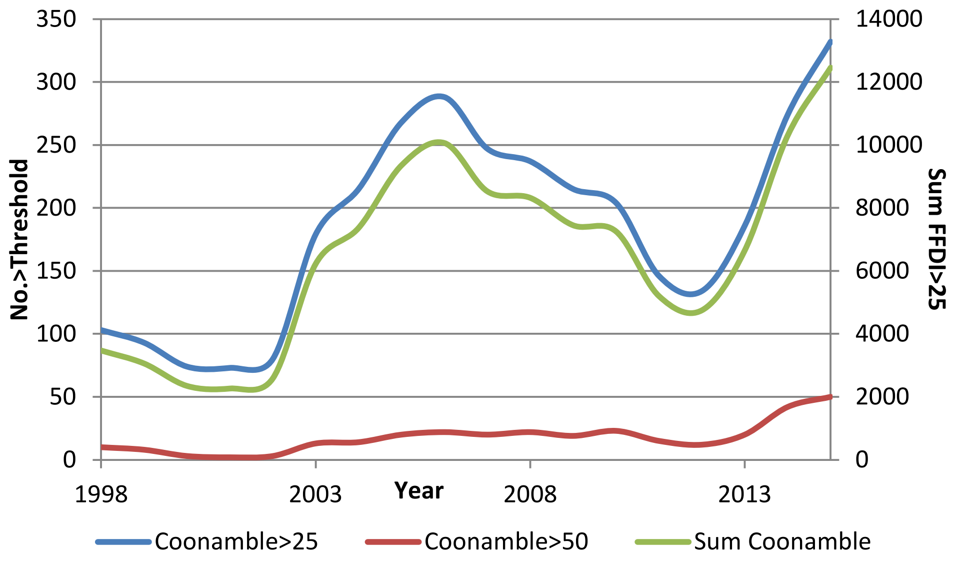
Moree

Years	No. FFDI>25	No. FFDI>50	∑FFDI>25
1994-98	67	2	2012
1995-99	57	2	1847
1996-00	49	1	1596
1997-01	54	1	1734
1998-02	45	1	1451
1999-03	89	1	2844
2000-04	112	1	3592
2001-05	122	2	3925
2002-06	133	4	4386
2003-07	110	3	3617
2004-08	103	3	3343
2005-09	166	8	5597
2006-10	187	11	6344
2007-11	160	11	5447
2008-12	151	11	5186
2009-13	120	10	4141
2010-14	160	18	5855
2011-15	215	27	8034
Av/yr	29.2	1.6	985.4



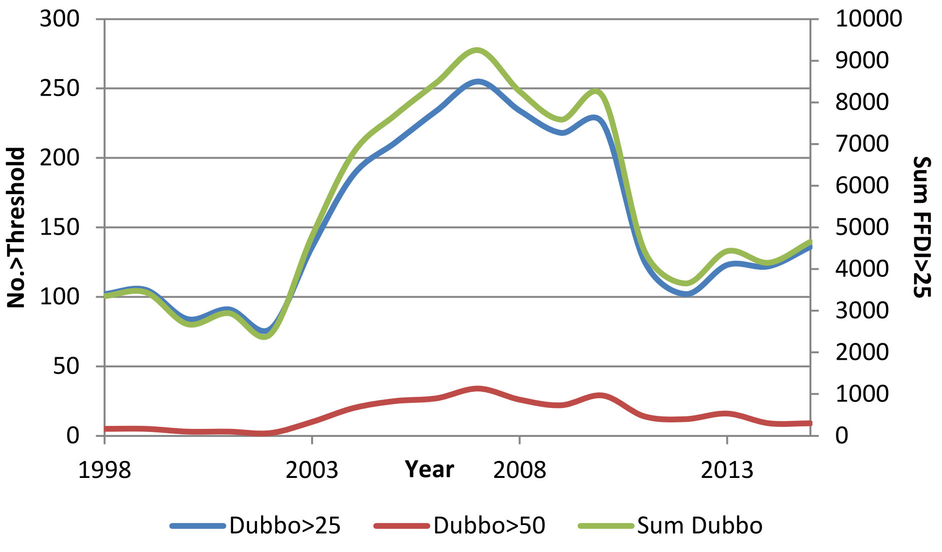
Coonamble

Years	No. FFDI>25	No. FFDI>50	∑FFDI>25
1994-98	103	10	3471
1995-99	93	8	3059
1996-00	74	3	2347
1997-01	73	2	2264
1998-02	80	3	2585
1999-03	179	13	6224
2000-04	215	14	7365
2001-05	268	20	9354
2002-06	288	22	10061
2003-07	247	20	8526
2004-08	237	22	8320
2005-09	215	19	7448
2006-10	204	23	7253
2007-11	146	15	5199
2008-12	134	12	4749
2009-13	186	20	6654
2010-14	274	42	10301
2011-15	332	50	12455
Av/yr	46.5	4.4	1633.8



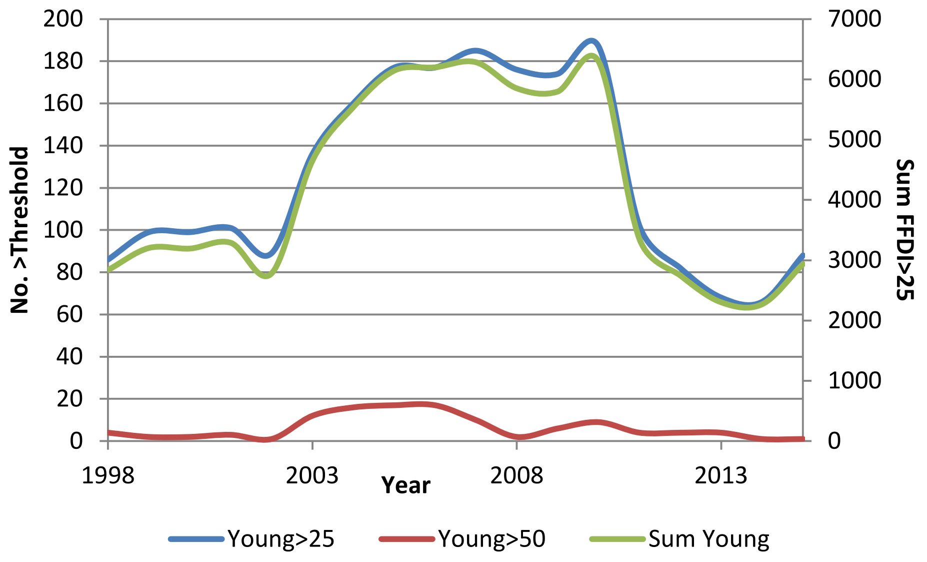
Dubbo

Years	No. FFDI>25	No. FFDI>50	∑FFDI>25
1994-98	102	5	3352
1995-99	105	5	3440
1996-00	84	3	2677
1997-01	91	3	2940
1998-02	77	2	2441
1999-03	136	10	4793
2000-04	188	20	6797
2001-05	211	25	7694
2002-06	234	27	8477
2003-07	255	34	9253
2004-08	234	26	8262
2005-09	218	22	7586
2006-10	225	29	8144
2007-11	126	14	4446
2008-12	102	12	3655
2009-13	123	16	4431
2010-14	122	9	4152
2011-15	136	9	4653
Av/yr	38.5	3.8	1349.9



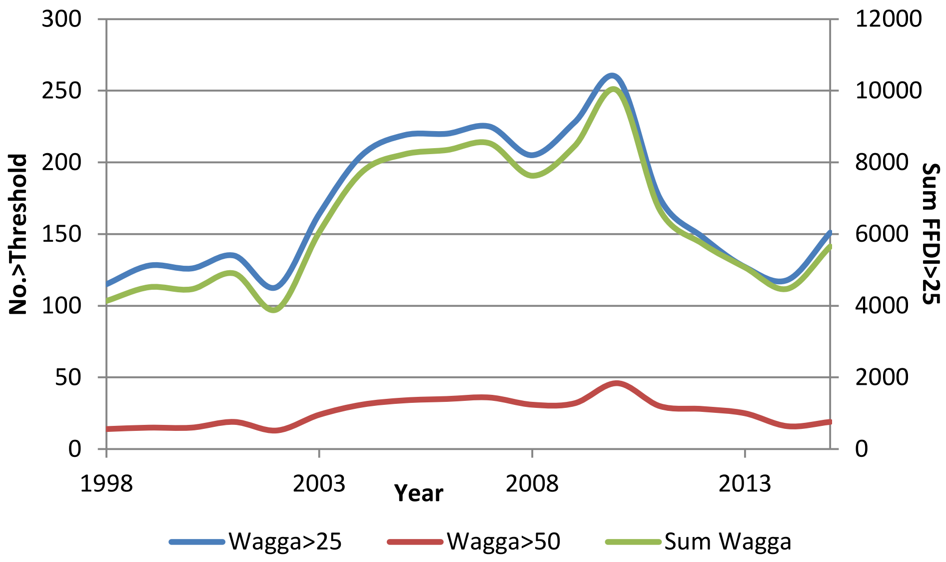
Young

Years	No. FFDI>25	No. FFDI>50	∑FFDI>25
1994-98	86	4	2837
1995-99	99	2	3203
1996-00	99	2	3193
1997-01	101	3	3290
1998-02	89	1	2780
1999-03	136	12	4650
2000-04	160	16	5538
2001-05	177	17	6143
2002-06	177	17	6199
2003-07	185	10	6283
2004-08	176	2	5850
2005-09	174	6	5797
2006-10	187	9	6296
2007-11	102	4	3351
2008-12	82	4	2746
2009-13	68	4	2302
2010-14	66	1	2270
2011-15	88	1	2936
Av/yr	31.3	1.6	1050.9



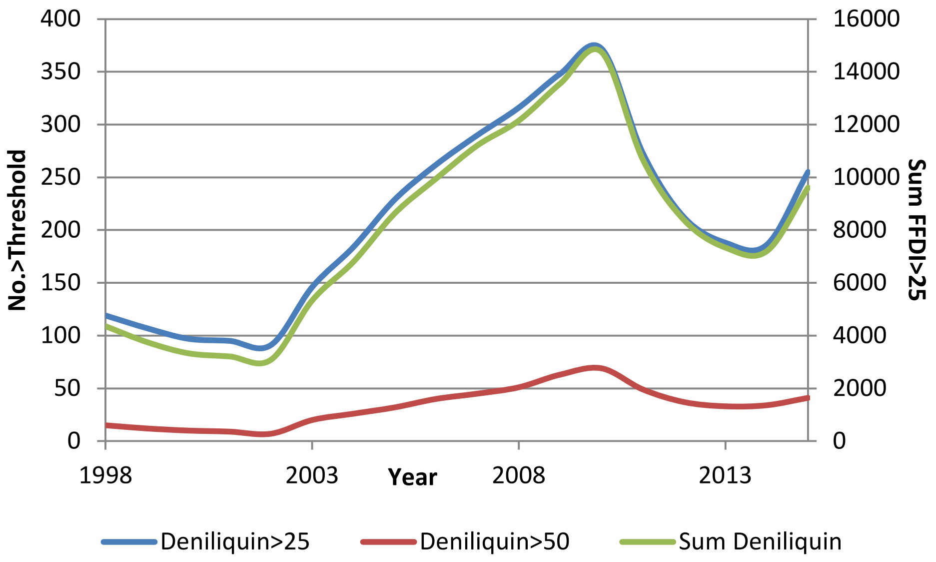
Wagga Wagga

Years	No. FFDI>25	No. FFDI>50	∑FFDI>25
1994-98	115	14	4134
1995-99	128	15	4518
1996-00	126	15	4461
1997-01	135	19	4902
1998-02	113	13	3897
1999-03	164	24	6051
2000-04	205	31	7727
2001-05	219	34	8226
2002-06	220	35	8345
2003-07	225	36	8533
2004-08	205	31	7627
2005-09	228	32	8458
2006-10	259	46	10006
2007-11	175	30	6672
2008-12	148	28	5732
2009-13	127	25	5068
2010-14	118	16	4474
2011-15	151	19	5652
Av/yr	42.5	6.4	1590.0



Deniliquin

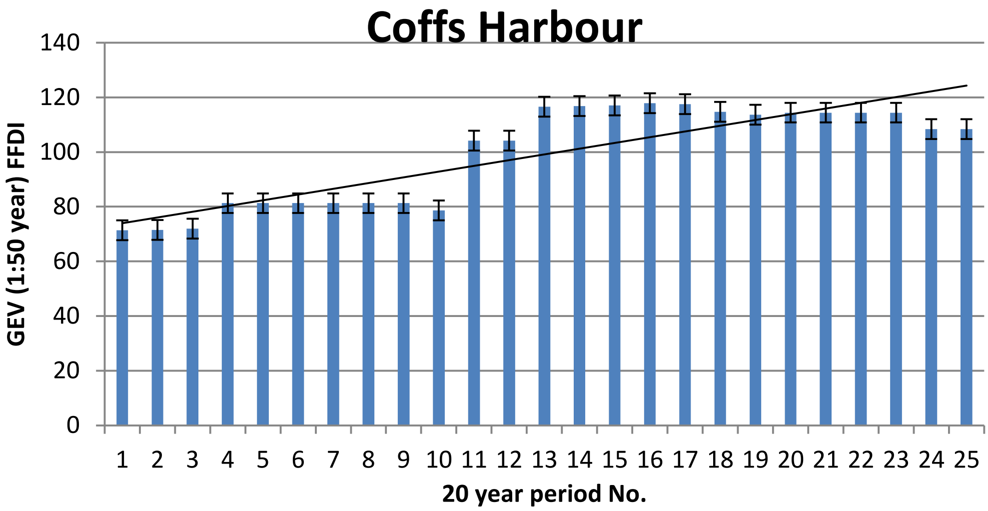
Years	No. FFDI>25	No. FFDI>50	∑FFDI>25
1994-98	119	15	4354
1995-99	107	12	3754
1996-00	97	10	3330
1997-01	95	9	3210
1998-02	91	7	3081
1999-03	146	20	5333
2000-04	184	26	6801
2001-05	229	32	8635
2002-06	262	40	9951
2003-07	290	45	11210
2004-08	316	51	12148
2005-09	348	63	13550
2006-10	372	69	14749
2007-11	273	49	10678
2008-12	212	37	8378
2009-13	188	33	7335
2010-14	186	34	7198
2011-15	255	41	9609
Av/yr	52.4	8.2	1990.3



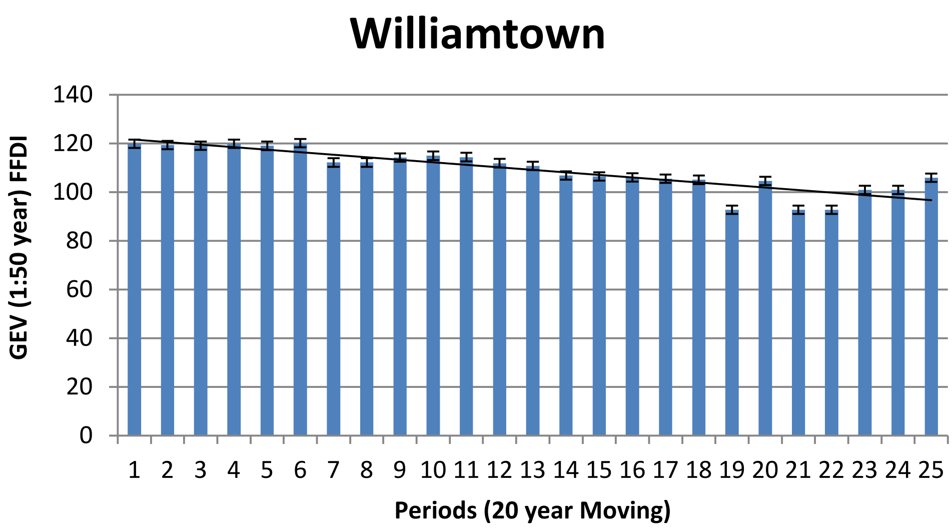
APPENDIX 15 - Moving 20 year averages of GEV_{50}FFDI*

*Appendix 17 provides the standard error results for all 20 year moving periods.

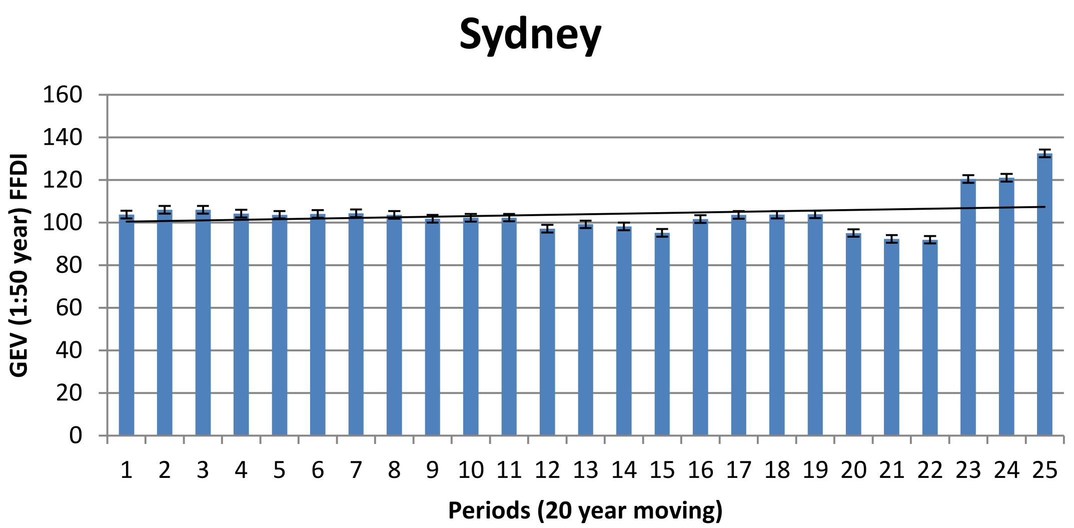
Coffs Harbour				FFDI	Count	Count	Sum
Year	α	β	r^2	GEV_{50}	>25	>50	FFDI
1972-92	11.916	24.757	0.9453	71	30	2	971
1973-93	11.979	24.654	0.9479	72	30	2	968
1974-94	11.798	25.814	0.9603	72	32	2	1043
1975-95	13.525	28.383	0.9725	81	34	3	1188
1976-96	13.525	28.383	0.9725	81	34	3	1188
1977-97	13.525	28.383	0.9725	81	35	3	1217
1978-98	13.525	28.383	0.9725	81	34	3	1192
1979-99	13.525	28.383	0.9725	81	34	3	1192
1980-2000	13.525	28.383	0.9725	81	34	3	1192
1981-2001	13.599	25.461	0.9439	79	29	2	990
1982-2002	20.686	23.247	0.9507	104	31	4	1131
1983-2003	20.686	23.247	0.9507	104	32	4	1158
1984-2004	23.314	25.401	0.9702	117	34	6	1308
1985-2005	23.41	25.221	0.9704	117	32	6	1253
1986-2006	23.555	24.949	0.9707	117	32	6	1250
1987-2007	23.998	24.034	0.9695	118	29	6	1158
1988-2008	23.819	24.335	0.9671	118	32	6	1244
1989-2009	23.49	22.817	0.9641	115	31	5	1178
1990-2010	22.695	24.9	0.9727	114	34	5	1296
1991-2011	23.064	24.198	0.9741	114	34	5	1296
1992-2012	23.064	24.198	0.9741	114	30	5	1177
1993-2013	23.064	24.198	0.9741	114	31	5	1215
1994-2014	23.064	24.198	0.9741	114	31	5	1215
1995-2015	22.556	20.166	0.9081	108	25	4	946
Overall	22.556	20.166	0.9081	108	25	4	946
Average	17.222	23.336	0.9628	91			
Year				99			



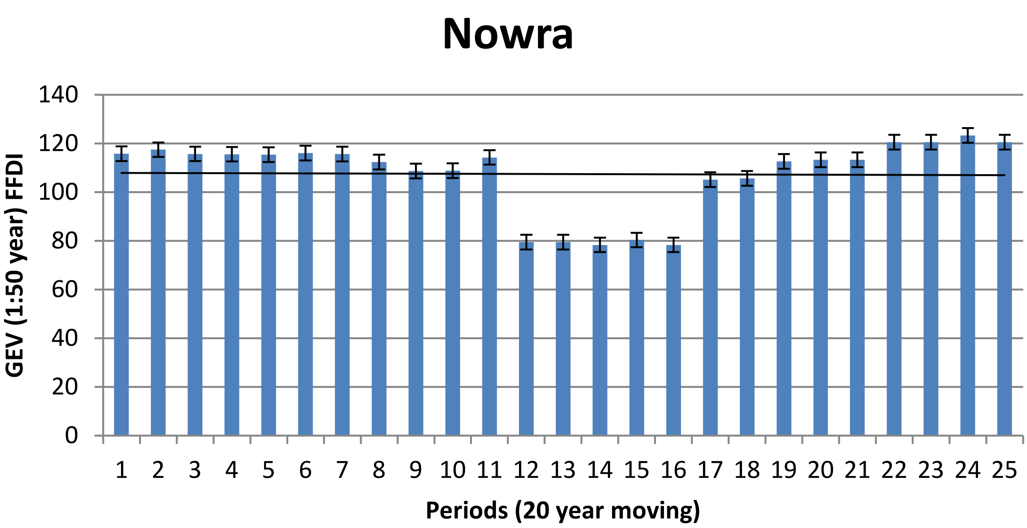
Williamtown				FFDI	Count	Count	Sum
Year	α	β	r^2	GEV_{50}	>25	>50	FFDI
1972-92	17.09	52.995	0.9714	120	164	21	6181
1973-93	17.523	50.755	0.9724	119	164	20	6144
1974-94	16.676	53.789	0.9719	119	175	23	6588
1975-95	17.09	52.995	0.9714	120	185	23	6869
1976-96	17.305	51.281	0.9753	119	190	22	6978
1977-97	17.785	50.476	0.9736	120	190	20	6903
1978-98	15.704	50.696	0.9821	112	192	20	6911
1979-99	15.704	50.696	0.9821	112	192	20	6911
1980-2000	16.92	47.955	0.9775	114	183	18	6523
1981-2001	17.56	46.199	0.9829	115	177	17	6238
1982-2002	15.902	52.140	0.9285	114	180	21	6509
1983-2003	14.746	54.161	0.9534	112	185	26	6801
1984-2004	14.173	55.287	0.9587	111	204	29	7462
1985-2005	12.893	56.370	0.9378	107	209	31	7647
1986-2006	12.567	57.230	0.9193	106	222	31	8062
1987-2007	12.38	57.538	0.9233	106	226	32	8208
1988-2008	12.125	58.001	0.9279	105	231	36	8464
1989-2009	12.334	56.769	0.937	105	231	35	8406
1990-2010	8.9661	57.649	0.8903	93	248	37	9011
1991-2011	12.125	57.144	0.9392	105	241	37	8778
1992-2012	8.9661	57.649	0.8903	93	230	35	8329
1993-2013	8.9661	57.649	0.8903	93	242	36	8814
1994-2014	10.669	59.097	0.9798	101	263	43	9781
1995-2015	10.669	59.097	0.9798	101	253	39	9390
Overall	11.785	59.778	0.9705	106	255	41	9541
Average	12.96	56.834	0.9846	108			
Year				109			



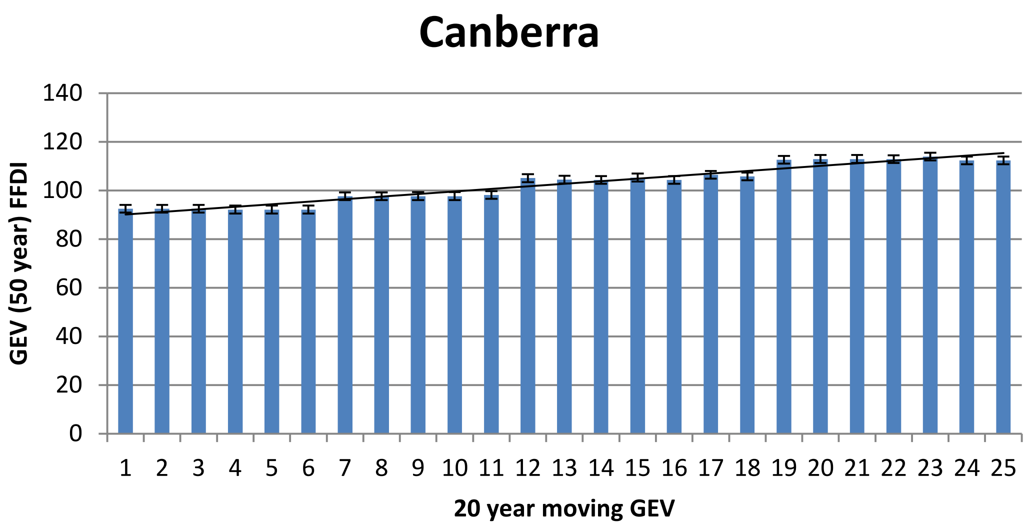
Sydney				FFDI	Count	Count	Sum
Year	α	β	r^2	GEV_{50}	>25	>50	FFDI
1972-92	13.572	50.580	0.9822	104	126	23	4753
1973-93	14.848	47.822	0.9789	106	118	20	4396
1974-94	14.848	47.822	0.9789	106	117	20	4372
1975-95	14.158	48.824	0.9814	104	128	21	4750
1976-96	14.277	47.766	0.9716	104	129	20	4740
1977-97	14.277	48.195	0.9749	104	131	19	4775
1978-98	14.239	48.562	0.972	104	131	19	4796
1979-99	13.878	49.261	0.9698	104	135	20	4979
1980-2000	13.698	48.135	0.9576	102	131	18	4776
1981-2001	13.885	47.827	0.9583	102	116	17	4296
1982-2002	13.594	49.084	0.9651	102	113	18	4221
1983-2003	11.648	51.518	0.9128	97	130	22	4909
1984-2004	12.712	49.387	0.934	99	138	19	5114
1985-2005	11.984	51.221	0.9252	98	150	21	5574
1986-2006	11.57	49.824	0.8718	95	157	19	5710
1987-2007	12.524	52.648	0.9557	102	167	22	6156
1988-2008	12.467	54.842	0.9734	104	173	27	6497
1989-2009	12.377	55.207	0.9704	104	174	26	6544
1990-2010	12.444	55.101	0.9702	104	163	25	6185
1991-2011	10.344	54.584	0.954	95	159	23	5963
1992-2012	9.0117	57.038	0.9541	92	177	28	6677
1993-2013	8.8161	57.401	0.9542	92	190	30	7202
1994-2014	15.51	59.725	0.9813	120	206	39	8116
1995-2015	15.755	59.317	0.9854	121	204	39	8038
Overall	18.547	59.803	0.9728	132	208	42	8293
Average	17.201	48.737	0.9825	116			
Year				104			



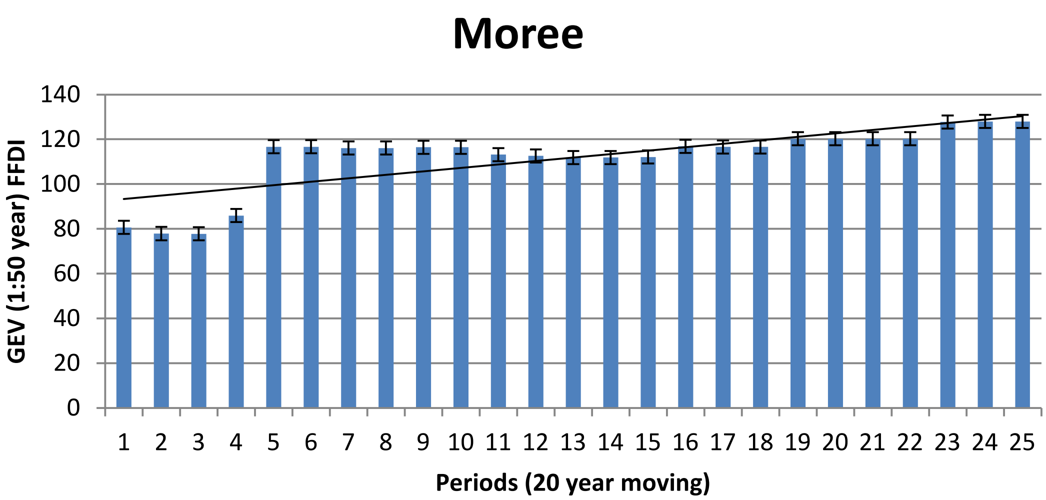
Nowra				FFDI	Count	Count	Sum
Year	α	β	r^2	GEV_{50}	≥25	≥50	FFDI
1972-92	17.777	46.150	0.86	116	145	18	5480
1973-93	18.572	44.733	0.8809	117	140	16	5245
1974-94	17.72	46.343	0.8585	116	150	18	5642
1975-95	17.661	46.443	0.8572	116	158	19	5880
1976-96	17.599	46.545	0.8556	115	161	20	5996
1977-97	17.903	45.991	0.864	116	164	19	6055
1978-98	17.699	46.409	0.8573	116	167	19	6179
1979-99	17.322	44.552	0.8169	112	163	17	5949
1980-2000	16.868	42.667	0.7652	109	153	14	5505
1981-2001	17.277	41.211	0.7723	109	146	12	5236
1982-2002	16.65	49.084	0.7631	114	154	16	5617
1983-2003	7.6229	49.550	0.8497	79	161	17	5846
1984-2004	7.6229	49.550	0.8497	79	170	17	6165
1985-2005	7.4252	49.249	0.8976	78	171	17	6158
1986-2006	7.7185	50.085	0.9032	80	181	19	6476
1987-2007	13.807	48.991	0.8578	78	190	22	6939
1988-2008	14.381	48.817	0.8922	105	192	22	7040
1989-2009	14.75	47.920	0.9019	106	193	21	7010
1990-2010	15.755	50.984	0.9693	113	205	25	7549
1991-2011	16.162	50.054	0.9747	113	195	25	7200
1992-2012	16.162	50.054	0.9747	113	185	25	6900
1993-2013	17.446	52.252	0.9913	121	194	27	7340
1994-2014	17.377	52.456	0.9892	120	195	26	7335
1995-2015	17.442	55.018	0.9845	123	189	25	7155
Overall	17.377	52.456	0.9892	120	198	27	7563
Average	16.944	49.864	0.9854	116			
Year				107			



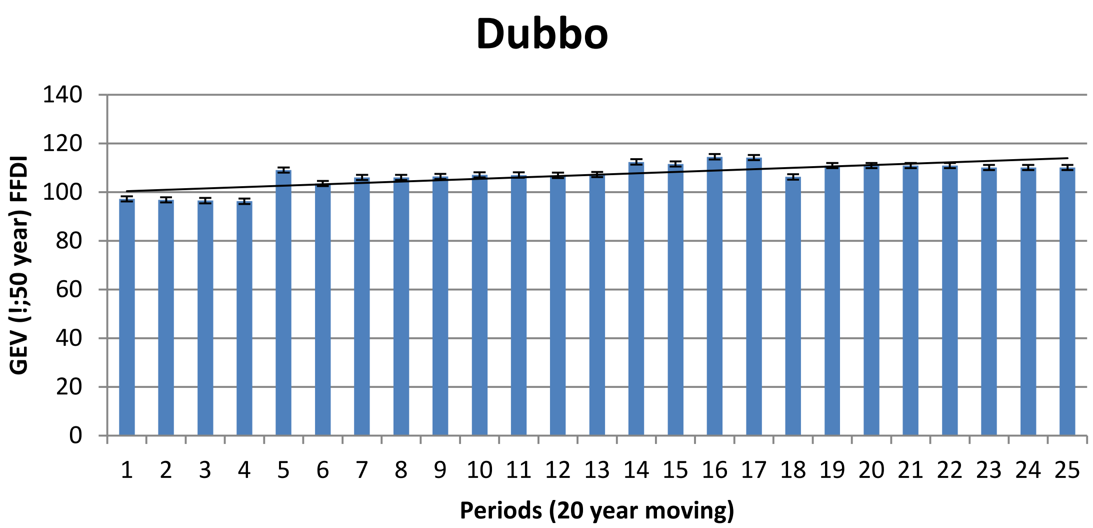
Canberra				FFDI	Count	Count	Sum
Year	α	β	r^2	GEV_{50}	>25	>50	FFDI
1972-92	10.816	50.157	0.9783	92	302	33	10621
1973-93	10.816	50.157	0.9783	92	287	33	10092
1974-94	10.816	50.157	0.9783	92	292	33	10232
1975-95	10.615	50.573	0.8574	92	295	34	10332
1976-96	10.615	50.573	0.8574	92	295	34	10329
1977-97	10.615	50.573	0.8574	92	295	34	10256
1978-98	11.633	52.102	0.9468	98	339	37	11967
1979-99	11.633	52.102	0.9468	98	334	35	11712
1980-2000	11.973	50.802	0.9464	98	317	33	11091
1981-2001	11.973	50.802	0.9464	98	307	31	10736
1982-2002	12.303	49.987	0.9516	98	302	29	10446
1983-2003	15.107	45.938	0.9612	105	268	18	9011
1984-2004	14.777	46.610	0.9557	104	291	19	9721
1985-2005	14.888	46.036	0.9488	104	278	19	9279
1986-2006	15.369	45.135	0.9598	105	287	17	9520
1987-2007	14.978	47.766	0.9564	104	320	21	10687
1988-2008	14.978	47.766	0.9564	106	315	21	10516
1989-2009	14.694	48.255	0.9502	106	342	23	11452
1990-2010	16.063	49.712	0.9717	113	365	27	12418
1991-2011	16.226	49.426	0.9745	113	341	26	11633
1992-2012	16.226	49.426	0.9745	113	339	26	11574
1993-2013	15.758	51.220	0.978	113	354	29	12140
1994-2014	15.68	52.551	0.9842	114	377	33	12999
1995-2015	15.384	52.169	0.9851	112	374	32	12907
Overall	15.384	52.169	0.9851	112	382	32	13177
Average	12.691	50.403	0.9783	100			
Year				103			



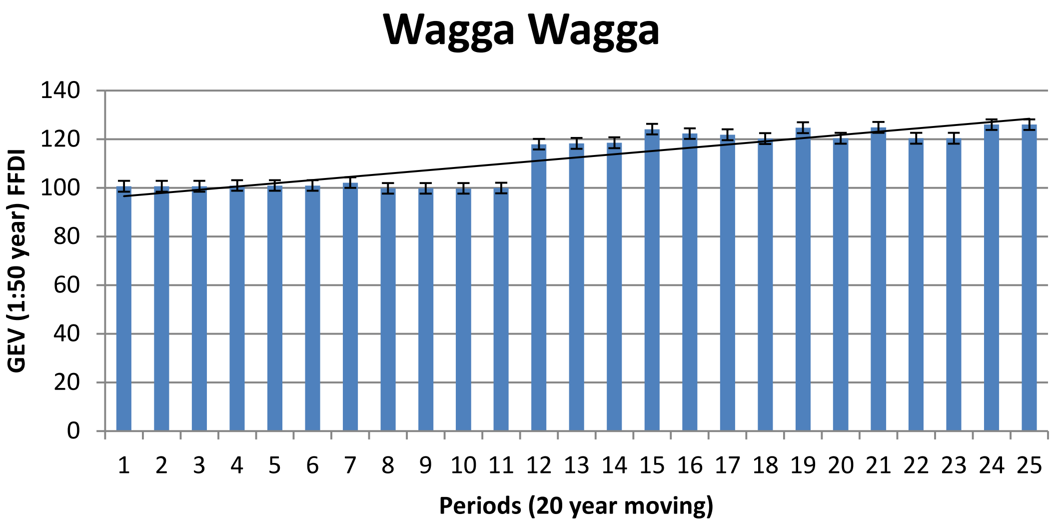
Moree				FFDI	Count	Count	Sum
Year	α	β	r^2	GEV_{50}	>25	>50	FFDI
1972-92	8.4736	47.465	0.8625	81	414	17	13440
1973-93	7.8353	47.22	0.7842	78	403	16	13049
1974-94	7.0669	50.137	0.7737	78	423	23	13883
1975-95	9.3108	49.535	0.9171	86	462	23	15134
1976-96	16.994	50.223	0.9237	117	473	30	15819
1977-97	16.994	50.223	0.9237	117	473	30	15819
1978-98	16.327	52.241	0.9274	116	512	36	17177
1979-99	16.327	52.241	0.9274	116	520	36	17418
1980-2000	16.481	51.962	0.903	116	481	33	16133
1981-2001	16.481	51.962	0.903	116	459	34	15366
1982-2002	15.478	52.61	0.8986	113	479	36	16124
1983-2003	14.583	55.544	0.8804	113	537	44	18254
1984-2004	14.192	56.365	0.8698	112	588	46	19937
1985-2005	14.192	56.365	0.8698	112	617	48	20831
1986-2006	13.899	57.72	0.8702	112	668	54	22649
1987-2007	14.663	59.521	0.925	117	725	57	24641
1988-2008	14.542	59.723	0.9247	117	752	60	25647
1989-2009	14.542	59.723	0.9247	117	761	62	25988
1990-2010	14.4	63.896	0.9609	120	817	76	28339
1991-2011	14.4	63.896	0.9609	120	792	75	27476
1992-2012	14.4	63.896	0.9609	120	784	74	27204
1993-2013	14.4	63.896	0.9609	120	824	79	28706
1994-2014	15.797	65.948	0.9456	128	885	85	31075
1995-2015	15.487	67.412	0.9613	128	909	92	32204
Overall	15.487	67.412	0.9613	128	919	95	32694
Average	13.803	60.04	0.9711	114	737	35	49587
Year				111			



Dubbo				FFDI	Count	Count	Sum
Year	α	β	r^2	GEV_{50}	>25	>50	FFDI
1972-92	14.892	38.889	0.8513	97	243	7	7875
1973-93	14.953	38.312	0.8408	97	233	6	7524
1974-94	14.75	38.777	0.8341	96	244	6	7875
1975-95	14.629	38.979	0.8284	96	259	6	8300
1976-96	17.857	39.174	0.905	109	282	8	9105
1977-97	16.523	38.83	0.8412	103	284	7	9083
1978-98	16.682	40.784	0.8936	106	323	10	10413
1979-99	16.682	40.784	0.8936	106	331	10	10645
1980-2000	16.857	40.487	0.8996	106	321	10	10307
1981-2001	17.22	39.69	0.9055	107	326	9	10424
1982-2002	16.944	40.695	0.912	107	347	11	11130
1983-2003	15.281	47.07	0.912	107	393	18	12986
1984-2004	14.267	51.347	0.9297	107	456	29	15330
1985-2005	15.076	53.394	0.9663	112	490	33	16609
1986-2006	14.667	54.184	0.961	112	523	37	17743
1987-2007	14.484	57.821	0.979	114	612	52	21138
1988-2008	14.165	58.77	0.9839	114	629	54	21765
1989-2009	12.164	58.633	0.973	106	644	54	22190
1990-2010	12.655	61.342	0.9843	111	681	65	23750
1991-2011	12.655	61.342	0.9843	111	670	63	23367
1992-2012	12.655	61.342	0.9843	111	666	63	23244
1993-2013	12.655	61.342	0.9843	111	713	68	24861
1994-2014	12.293	61.948	0.981	110	754	72	26358
1995-2015	12.293	61.948	0.981	110	758	72	26583
Overall	12.293	61.948	0.981	110	758	72	26621
Average	12.45	55.115	0.9834	104			
Year				107			

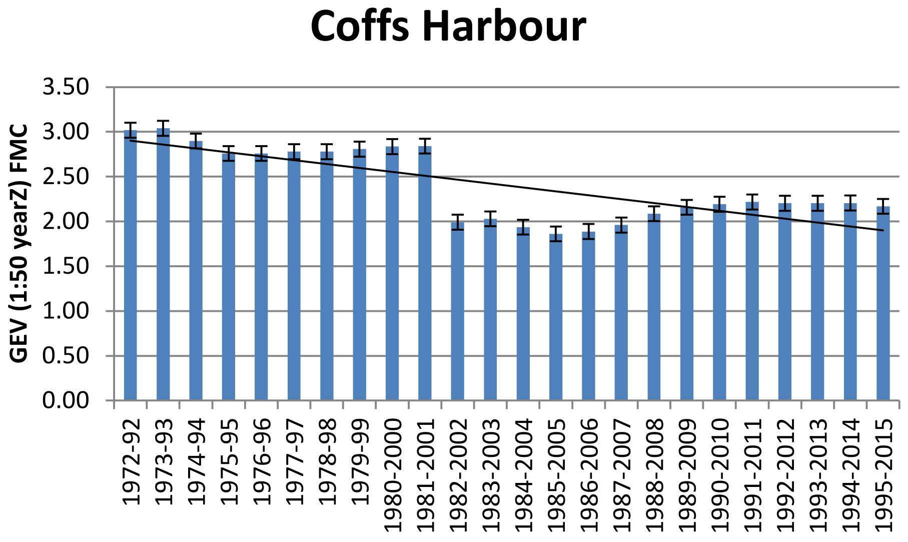


Wagga Wagga				FFDI	Count	Count	Sum
Year	*α*	*β*	r^2	GEV_{50}	>25	>50	FFDI
1972-92	13.406	62.631	0.9891	101	549	60	19700
1973-93	13.406	62.631	0.9891	101	535	58	19197
1974-94	13.406	62.631	0.9891	101	538	58	19310
1975-95	13.167	63.605	0.9914	101	551	61	19845
1976-96	13.167	63.605	0.9914	101	557	61	20035
1977-97	13.167	63.605	0.9914	101	559	62	20117
1978-98	13.941	62.587	0.9827	102	584	69	21138
1979-99	13.729	60.87	0.9774	100	577	65	20697
1980-2000	13.729	60.87	0.9774	100	539	63	19436
1981-2001	13.731	60.82	0.9335	100	545	66	19726
1982-2002	13.924	60.459	0.976	100	547	64	19731
1983-2003	22.044	55.428	0.9289	118	553	65	19894
1984-2004	21.463	57.417	0.9335	118	616	74	22290
1985-2005	21.271	58.252	0.9351	119	608	77	22037
1986-2006	22.973	58.987	0.9729	124	631	79	22902
1987-2007	21.016	62.717	0.9502	122	699	94	25685
1988-2008	20.591	63.473	0.9424	122	702	95	25817
1989-2009	19.096	66.128	0.9065	120	763	105	28096
1990-2010	19.855	68.457	0.9442	125	805	119	30015
1991-2011	18.864	66.904	0.8769	120	748	112	27907
1992-2012	18.864	66.904	0.8769	125	728	110	27093
1993-2013	19.855	68.6	0.9458	120	767	115	28656
1994-2014	19.638	69.173	0.9479	120	828	124	30946
1995-2015	19.695	70.169	0.9634	126	849	124	31662
Overall	19.695	70.169	0.9634	126	862	125	32095
Average	15.758	66.896	0.9416	112			
Year	16.69	61.85		109			

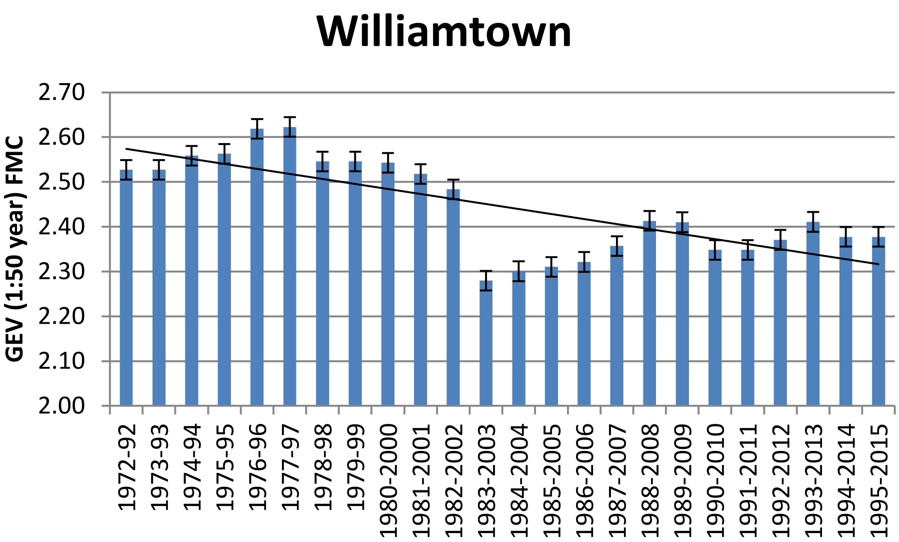


APPENDIX 16 -Moving 20 year GEV_{50} FMC

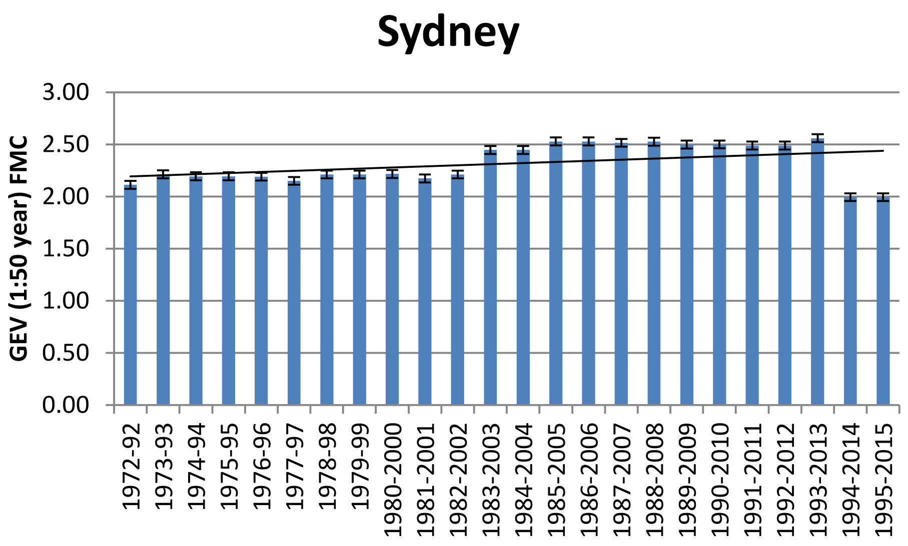
Coffs Hbr				FMC
Year	α	β	r^2	GEV_{50}
1972-92	-0.507	5.0018	0.9862	3.02
1973-93	-0.495	4.976	0.9868	3.04
1974-94	-0.521	4.9359	0.9799	2.90
1975-95	-0.543	4.8819	0.9456	2.76
1976-96	-0.543	4.8819	0.9456	2.76
1977-97	-0.548	4.9221	0.9586	2.78
1978-98	-0.548	4.9221	0.9586	2.78
1979-99	-0.528	4.8729	0.953	2.81
1980-2000	-0.541	4.9523	0.9567	2.84
1981-2001	-0.563	5.0438	0.9505	2.84
1982-2002	-0.756	4.9484	0.976	1.99
1983-2003	-0.731	4.8896	0.9738	2.03
1984-2004	-0.714	4.7287	0.9463	1.94
1985-2005	-0.75	4.7956	0.9422	1.86
1986-2006	-0.735	4.7627	0.935	1.89
1987-2007	-0.7	4.6984	0.9355	1.96
1988-2008	-0.643	4.6017	0.9567	2.09
1989-2009	-0.63	4.6214	0.9685	2.16
1990-2010	-0.581	4.4651	0.9673	2.19
1991-2011	-0.568	4.4391	0.9706	2.22
1992-2012	-0.574	4.4487	0.9726	2.20
1993-2013	-0.574	4.4487	0.9726	2.20
1994-2014	-0.585	4.4941	0.9706	2.21
1995-2015	-0.618	4.5867	0.9682	2.17
Overall	-0.726	5.2795	0.9745	2.44
Average				2.40



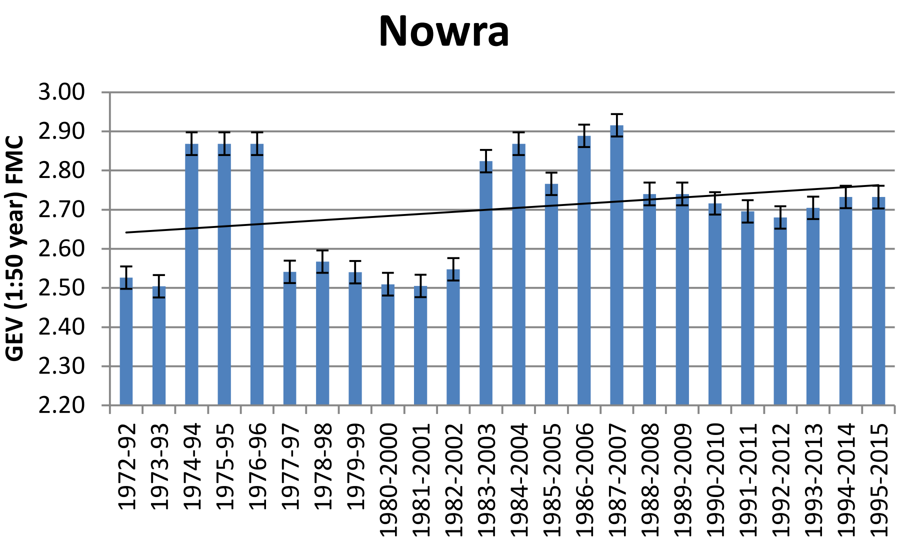
Williamtown				FMC
Year	α	β	r^2	GEV_{50}
1972-92	-0.381	4.0176	0.9664	2.53
1973-93	-0.381	4.0176	0.9664	2.53
1974-94	-0.362	3.9748	0.9632	2.56
1975-95	-0.359	3.9673	0.9625	2.56
1976-96	-0.351	3.9917	0.9438	2.62
1977-97	-0.347	3.9801	0.9392	2.62
1978-98	-0.364	3.9698	0.9591	2.55
1979-99	-0.364	3.9698	0.9591	2.55
1980-2000	-0.364	3.9668	0.9596	2.54
1981-2001	-0.375	3.9849	0.9637	2.52
1982-2002	-0.343	3.8254	0.9585	2.48
1983-2003	-0.364	3.7036	0.9676	2.28
1984-2004	-0.353	3.6817	0.9698	2.30
1985-2005	-0.338	3.6327	0.9735	2.31
1986-2006	-0.333	3.6241	0.9749	2.32
1987-2007	-0.309	3.5658	0.9776	2.36
1988-2008	-0.275	3.4889	0.9832	2.41
1989-2009	-0.276	3.4899	0.9824	2.41
1990-2010	-0.279	3.4398	0.9632	2.35
1991-2011	-0.279	3.4398	0.9632	2.35
1992-2012	-0.28	3.4662	0.9663	2.37
1993-2013	-0.252	3.3966	0.9573	2.41
1994-2014	-0.246	3.3399	0.9373	2.38
1995-2015	-0.246	3.3399	0.9373	2.38
Overall	-0.274	3.5235	0.9551	2.45
Mean				2.44



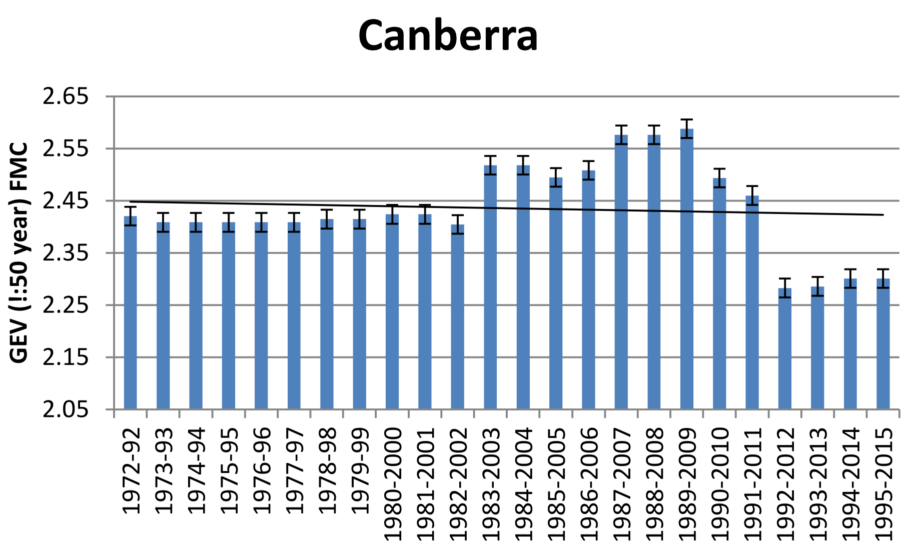
Sydney				FMC
Year	α	β	r^2	GEV_{50}
1972-92	-0.41	3.7159	0.9793	2.11
1973-93	-0.397	3.765	0.9736	2.21
1974-94	-0.391	3.7233	0.9831	2.19
1975-95	-0.391	3.7233	0.9831	2.19
1976-96	-0.392	3.7234	0.9835	2.19
1977-97	-0.41	3.7535	0.9871	2.15
1978-98	-0.371	3.663	0.9512	2.21
1979-99	-0.371	3.663	0.9512	2.21
1980-2000	-0.393	3.754	0.9594	2.22
1981-2001	-0.414	3.7933	0.96	2.17
1982-2002	-0.371	3.663	0.9512	2.21
1983-2003	-0.302	3.6275	0.92	2.45
1984-2004	-0.302	3.6275	0.92	2.45
1985-2005	-0.265	3.565	0.9521	2.53
1986-2006	-0.265	3.565	0.9521	2.53
1987-2007	-0.259	3.5275	0.9335	2.51
1988-2008	-0.238	3.4574	0.9175	2.53
1989-2009	-0.255	3.4951	0.918	2.50
1990-2010	-0.237	3.4265	0.9145	2.50
1991-2011	-0.242	3.435	0.9036	2.49
1992-2012	-0.242	3.435	0.9036	2.49
1993-2013	-0.202	3.3487	0.9202	2.56
1994-2014	-0.349	3.3588	0.9581	1.99
1995-2015	-0.349	3.3588	0.9581	1.99
Overall	-0.329	3.4489	0.9735	2.16
Mean				2.32



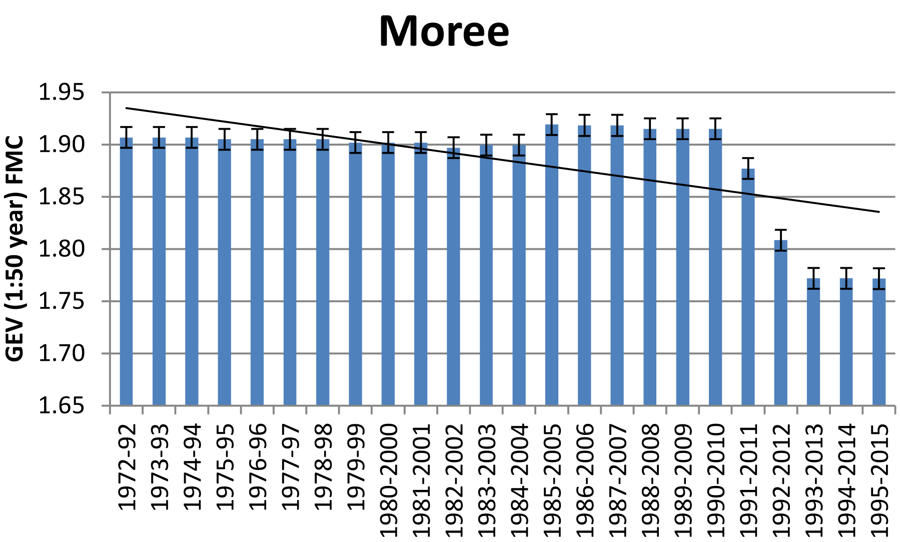
Nowra				FMC
Year	α	β	r^2	GEV_{50}
1972-92	-0.317	3.7666	0.9885	2.53
1973-93	-0.327	3.7837	0.986	2.50
1974-94	-0.219	3.7252	0.9526	2.87
1975-95	-0.219	3.7252	0.9526	2.87
1976-96	-0.32	3.773	0.9896	2.87
1977-97	-0.307	3.7423	0.9849	2.54
1978-98	-0.294	3.7172	0.9834	2.57
1979-99	-0.316	3.7765	0.9923	2.54
1980-2000	-0.33	3.8006	0.9874	2.51
1981-2001	-0.344	3.8507	0.9847	2.50
1982-2002	-0.321	3.8036	0.9793	2.55
1983-2003	-0.242	3.7709	0.9499	2.82
1984-2004	-0.219	3.7252	0.9526	2.87
1985-2005	-0.232	3.6738	0.9665	2.77
1986-2006	-0.196	3.6551	0.9395	2.89
1987-2007	-0.17	3.5803	0.9695	2.92
1988-2008	-0.216	3.5852	0.9733	2.74
1989-2009	-0.216	3.5852	0.9733	2.74
1990-2010	-0.217	3.5651	0.9838	2.72
1991-2011	-0.226	3.58	0.9875	2.70
1992-2012	-0.235	3.5995	0.9853	2.68
1993-2013	-0.221	3.5691	0.9911	2.70
1994-2014	-0.204	3.5307	0.9915	2.73
1995-2015	-0.2	3.5145	0.992	2.73
Overall	-0.218	3.5673	0.94	2.71
Mean				2.70



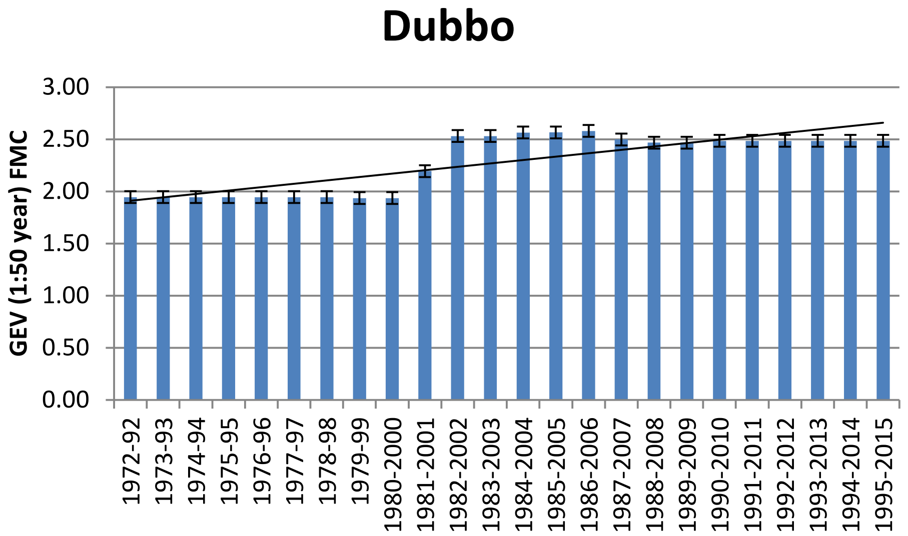
Canberra				FMC
Year	α	β	r^2	GEV_{50}
1972-92	-0.211	3.246	0.9452	2.42
1973-93	-0.22	3.25	0.94	2.41
1974-94	-0.22	3.25	0.94	2.41
1975-95	-0.22	3.25	0.94	2.41
1976-96	-0.22	3.25	0.94	2.41
1977-97	-0.22	3.25	0.94	2.41
1978-98	-0.196	3.1815	0.9138	2.41
1979-99	-0.196	3.1815	0.9138	2.41
1980-2000	-0.202	3.2142	0.9292	2.42
1981-2001	-0.202	3.2142	0.9292	2.42
1982-2002	-0.211	3.2301	0.9254	2.40
1983-2003	-0.223	3.3905	0.9402	2.52
1984-2004	-0.223	3.3905	0.9402	2.52
1985-2005	-0.235	3.4141	0.9343	2.49
1986-2006	-0.228	3.4	0.9382	2.51
1987-2007	-0.202	3.3665	0.9694	2.58
1988-2008	-0.202	3.3665	0.9694	2.58
1989-2009	-0.183	3.3038	0.9413	2.59
1990-2010	-0.179	3.1936	0.937	2.49
1991-2011	-0.197	3.2307	0.946	2.46
1992-2012	-0.243	3.2334	0.9787	2.28
1993-2013	-0.242	3.2326	0.9791	2.29
1994-2014	-0.233	3.2124	0.9716	2.30
1995-2015	-0.233	3.2124	0.9716	2.30
Overall	-0.206	3.2354	0.9644	2.43
Mean				2.44



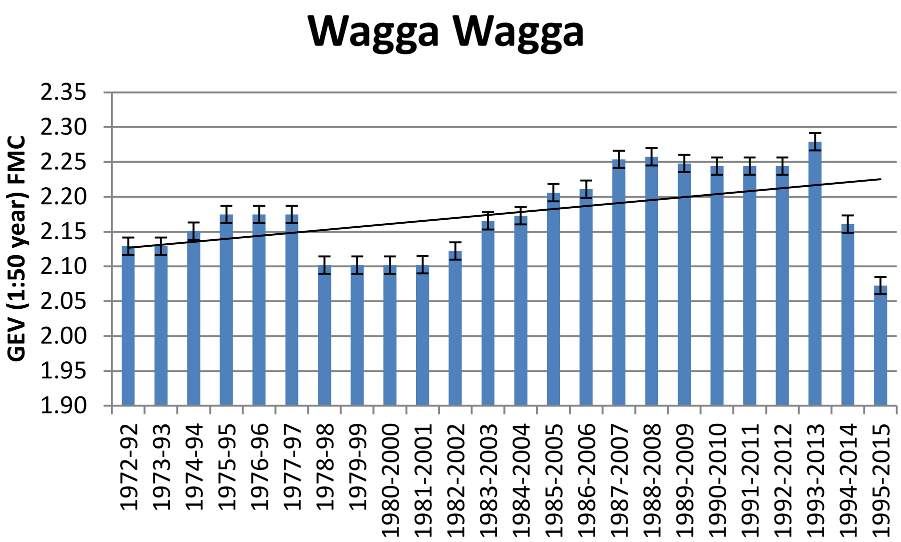
Moree				FMC
Year	α	β	r^2	GEV_{50}
1972-92	-0.023	1.9968	0.9538	1.91
1973-93	-0.023	1.9968	0.9538	1.91
1974-94	-0.023	1.9968	0.9538	1.91
1975-95	-0.024	1.999	0.9425	1.91
1976-96	-0.024	1.999	0.9425	1.91
1977-97	-0.024	1.999	0.9425	1.91
1978-98	-0.024	1.999	0.9425	1.91
1979-99	-0.024	1.9958	0.9319	1.90
1980-2000	-0.024	1.9958	0.9319	1.90
1981-2001	-0.024	1.9958	0.9319	1.90
1982-2002	-0.026	1.9987	0.9287	1.90
1983-2003	-0.032	2.0248	0.9458	1.90
1984-2004	-0.032	2.0248	0.9458	1.90
1985-2005	-0.03	2.0365	0.9864	1.92
1986-2006	-0.031	2.0396	0.9891	1.92
1987-2007	-0.031	2.0396	0.9891	1.92
1988-2008	-0.033	2.0441	0.9878	1.92
1989-2009	-0.033	2.0441	0.9878	1.92
1990-2010	-0.033	2.0441	0.9878	1.92
1991-2011	-0.059	2.1078	0.9293	1.88
1992-2012	-0.096	2.184	0.8996	1.81
1993-2013	-0.123	2.2532	0.9372	1.77
1994-2014	-0.123	2.2532	0.9372	1.77
1995-2015	-0.126	2.2647	0.9428	1.77
Overall	-0.03	2.0237	0.94	1.91
Mean				1.89



Dubbo				FMC
Year	α	β	r^2	GEV_{50}
1972-92	-0.034	2.0786	0.9719	1.95
1973-93	-0.034	2.0786	0.9719	1.95
1974-94	-0.034	2.0786	0.9719	1.95
1975-95	-0.034	2.0786	0.9719	1.95
1976-96	-0.034	2.0786	0.9719	1.95
1977-97	-0.034	2.0786	0.9719	1.95
1978-98	-0.034	2.0786	0.9719	1.95
1979-99	-0.04	2.0933	0.9719	1.94
1980-2000	-0.04	2.0933	0.9719	1.94
1981-2001	-0.279	3.2859	0.9114	2.19
1982-2002	-0.181	3.2394	0.9524	2.53
1983-2003	-0.166	3.1794	0.986	2.53
1984-2004	-0.144	3.1282	0.9841	2.56
1985-2005	-0.136	3.0983	0.9767	2.57
1986-2006	-0.126	3.0721	0.9833	2.58
1987-2007	-0.137	3.0343	0.9767	2.50
1988-2008	-0.142	3.024	0.9787	2.47
1989-2009	-0.142	3.024	0.9787	2.47
1990-2010	-0.126	2.977	0.9747	2.48
1991-2011	-0.126	2.977	0.9747	2.48
1992-2012	-0.126	2.977	0.9747	2.48
1993-2013	-0.123	2.9663	0.9756	2.49
1994-2014	-0.123	2.9663	0.9756	2.49
1995-2015	-0.123	2.9663	0.9756	2.49
Overall	-0.042	2.122	0.9626	1.96
Mean				2.27



Wagga Wagga				FMC
Year	α	β	r^2	GEV_{50}
1972-92	-0.197	2.8998	0.9184	2.13
1973-93	-0.197	2.8998	0.9184	2.13
1974-94	-0.187	2.8821	0.924	2.15
1975-95	-0.174	2.8552	0.9289	2.17
1976-96	-0.174	2.8552	0.9289	2.17
1977-97	-0.174	2.8552	0.9289	2.17
1978-98	-0.192	2.8531	0.9349	2.10
1979-99	-0.192	2.8531	0.9349	2.10
1980-2000	-0.192	2.8531	0.9349	2.10
1981-2001	-0.186	2.83	0.9185	2.10
1982-2002	-0.177	2.8147	0.9295	2.12
1983-2003	-0.164	2.8071	0.9703	2.17
1984-2004	-0.154	2.7751	0.9576	2.17
1985-2005	-0.149	2.7889	0.9744	2.21
1986-2006	-0.144	2.7743	0.9645	2.21
1987-2007	-0.12	2.7234	0.968	2.25
1988-2008	-0.118	2.7191	0.9633	2.26
1989-2009	-0.112	2.6858	0.973	2.25
1990-2010	-0.103	2.6472	0.9683	2.24
1991-2011	-0.108	2.6668	0.9774	2.24
1992-2012	-0.108	2.6668	0.9774	2.24
1993-2013	-0.104	2.6858	0.973	2.28
1994-2014	-0.125	2.6499	0.9953	2.16
1995-2015	-0.147	2.6478	0.9902	2.07
Overall	-0.14	2.7171	0.9814	2.17
Mean				2.18



APPENDIX 17: Standard Errors for 20 Year Moving Average and Overall GEV_{50} FFDI

Year	Coffs Harbour	Williamtown	Sydney	Nowra	Canberra	Moree	Dubbo	Wagga Wagga
1972-92	2.89	2.32	4.58	2.56	2.01	1.84	1.60	4.75
1973-93	0.31	2.39	1.48	3.22	2.01	2.34	1.60	4.75
1974-94	1.29	2.51	0.00	2.69	2.01	1.74	1.64	4.75
1975-95	2.23	2.54	1.03	2.61	1.88	2.41	1.57	4.82
1976-96	0.00	2.40	1.43	2.53	1.88	4.02	5.06	4.82
1977-97	0.33	2.47	1.00	2.76	1.85	4.02	4.29	4.82
1978-98	0.27	2.25	0.88	2.76	2.82	3.87	4.38	5.71
1979-99	0.00	2.25	0.76	3.05	2.58	3.87	4.38	4.93
1980-00	0.00	2.32	2.49	4.21	2.77	4.00	4.47	4.93
1981-01	1.76	2.28	0.47	3.78	2.77	4.00	4.63	4.94
1982-02	4.78	2.70	1.25	4.13	2.86	3.15	4.56	5.09
1983-03	0.26	2.49	2.31	5.02	3.80	3.71	4.36	3.87
1984-04	4.47	2.41	1.23	5.02	3.60	3.58	3.98	3.96
1985-05	0.37	2.30	1.06	4.45	3.56	3.58	5.55	4.23
1986-06	0.31	2.38	2.23	4.52	3.86	3.69	5.30	6.01
1987-07	0.73	2.32	3.00	3.50	4.54	3.69	6.18	4.56
1988-08	0.57	2.25	2.20	3.42	4.54	3.52	6.06	4.23
1989-09	2.65	2.10	0.80	3.41	4.33	3.52	5.63	3.18
1990-10	0.00	2.10	0.22	4.24	5.84	3.64	5.38	3.91
1991-11	0.00	2.04	2.19	4.38	5.95	3.64	5.38	3.86
1992-12	0.58	3.22	1.28	4.38	5.95	3.64	5.38	3.86
1993-13	0.69	3.22	0.37	6.52	6.03	3.64	5.38	5.15
1994-14	0.00	2.32	3.64	6.56	5.60	5.58	5.10	5.00
1995-15	4.23	2.19	0.50	6.56	5.78	5.50	5.10	5.45
Overall	3.40	4.56	3.62	3.41	3.69	3.67	4.12	3.15